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PASSIVE RADAR

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Abstract

The basic ideas and concepts of one of the newest branches of radar, that of passive radar, are discussed. A great deal of attention is devoted to questions of the use of passive radar by the armed forces. The physical fundamentals of passive radar, and the principles on which the construction of passive radars for different purposes are based, are elucidated. Examples of target characteristics, and the very simplest of calculation methods for making an approximate assessment of the service capabilities of passive radars, are cited. The materials contained in the book are from open Soviet and foreign sources. It is written for officers involved in the operation and combat use of radio engineering equipment, as well as for students in military schools. The book is of interest as well to other readers interested in modern radar equipment.

INTRODUCTION /3

The headlong development of radio electronics in recent years has led to the perfecting of existing radio engineering equipment, and to the appearance of completely new types of equipments as well. One such new type of radio engineering equipment is the passive radar, or as it still is called, passive thermal radar.

The passive radar is, in many respects, similar to the conventional radar. Like the latter, passive radars are designed to detect distant objects, and to fix their coordinates. The passive radar also is similar to conventional radar in the accessories used. Passive radars use antennas and receivers in the centimeter and millimeter bands, just as do conventional radars.

There is, however, one important difference, and it is this difference that places passive radar in a separate branch of radio electronics. This difference is associated with the nature of the radio-frequency (r-f) radiation used. Conventional radar makes use of special oscillators (magnetrons, power klystrons, and so on), but passive radar uses the natural r-f radiation from the target. This natural r-f radiation is thermal in origin in the majority of targets. It is this radiation that has come to be called thermal radio radiation, and this, in turn, has led to the coining of the term "passive radar."

Thermal radio radiation is inherent in all bodies with temperatures /4
above absolute zero.* The characteristics of this radiation, intensity, spectral makeup, and degree of polarization, will depend on the physical properties of the radiating body in absolute terms.

A passive radar thus can detect and fix the coordinates of the majority of natural and artificial bodies, and also can investigate their physical properties.

All of this is what makes passive radar an effective weapon for remote observation and monitoring.

Foreign military specialists believe that the combination of absolute secrecy and all-weather capability give passive radar definite advantages over conventional radar and the infrared (IR) technique. The intense development of measures designed to counter radar and IR equipment even further enhances the role of passive radar for military use in radio electronic complexes.

Foreign countries have built airborne passive radar for ground scanning, as well as navigation equipment for aircraft, warships, submarines, and spacecraft. Passive radar for guided missile homing, as well as certain other types of military passive radars, are in the experimental stage.

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*Absolute zero (zero temperature on an absolute scale) corresponds to a temperature of −273.1° on the Celsius scale. All temperatures in what follows will be given on the absolute scale.

Moreover, thermal radio radiation methods are coming into practical use in conventional radar operation. They have, for example, proven to be very convenient for calibrating and tuning the antennas of ground radar stations by using thermal radio radiation from natural sources.

Passive radar can be used to perform many national economy tasks, and in research, in addition to military uses.

These tasks can include, among others, ice reconnaissance, geological, geophysical, and meteorological research, and the detection of forest and underground fires. Passive radar methods are widely used in experimental physics, particularly in the study of plasma.

Passive radar appeared at the end of the 1940s. The rapid progress in the field is in no small way due to the efforts of Soviet scientists and engineers.

Professor S. M. Rytov, for example, undertook fundamental research in the field of the theory of thermal radio radiation. A. Ye. Basharinov provided the answers to a number of important theoretical questions dealing with passive radar. V. S. Troitskiy, L. T. Tuchkov, and a number of other Soviet researchers, were involved in research in thermal radio radiation from the terrestrial surface and atmosphere. F. V. Bunkin, V. V. Vitkevich, N. V. Karlov, A. A. Krasovskiy, A. G. Kislyakov, V. S. Troitskiy, N. M. Tseytlin, B. M. Chikhachev, and other Soviet scientists, made a great contribution to the theory of the reception of thermal radio radiation.

The physical principles of passive radar are summarized, functional diagrams of passive radars are described, as are the schematic features of the equipment, and recommendations are made for modifying radar receivers to receive natural r-f radiation. The concluding section of the book contains a survey of modern models of foreign equipment. Their military capabilities are described, and questions of the military and economic use of passive radar are considered.

A. G. Nikolayev wrote the sections on "Thermal Radio Radiation," "Passive Radar Methods," and "Use of Passive Radar." A. G. Nikolayev and S. V. Pertsov collaborated on the section on "Reception of Thermal Radio Radiation."

The book has shortcomings, of course, so suggestions and comments by readers will be appreciated.

The authors wish to express their thanks to all those who took part in discussing the manuscript, and to G. G. Khomenyuk, for his help in its organization.

1. Thermal Radio Radiation /6

The Physical Essence of Thermal Radiation and its Laws

The fact that a body, when heated to a high temperature, will radiate light, has been known since antiquity. Modern instruments, used to observe radiation, have established that heated bodies, in addition to light waves, radiate longer, infrared, waves. Scientists also have detected ultraviolet radiation, the wavelength of which is shorter than that of visible and infrared radiations, from these bodies. And by the end of the last century the physical nature of thermal radiation had been elucidated. As is known, any substance, solid, liquid, or gaseous, has associated with it a great many charged particles, electrons and positive ions, in addition to electrically neutral particles. These particles are in constant chaotic motion, and their mean velocity is greater the higher the temperature of the substance. The charged particles constantly collide with each other as they move about, as well as with neutral particles. The result of these collisons is to convert some of their kinetic energy into electromagnetic radiation energy. The velocity of the particles is somewhat reduced thereby.

Thus, the kinetic energy of the particles, which is proportional to the degree to which the body is heated, is partially converted into electromagnetic field energy. A very great many of the chaotically colliding particles take part in the generation of thermal radiation. A greater number of collisions take place at certain times, a lesser number at others. The kinetic energy also differs at different times as it is being converted into radiation.

So it is that radiation intensity is changing constantly, but /7
the magnitude and rate of such change cannot be predicted accurately. The same can be said of the spectral composition of the radiation. Because the frequency of the radiation occurring during the deceleration of the charged particles depends on their kinetic energy, the magnitude of which is different for different particles, radiation intensity at a predetermined frequency (spectral density of the radiation) also will fluctuate continuously and chaotically.

So it will be seen that thermal radiation differs from artifically generated radiation in that, first, it covers a very broad band of wavelengths and, second, its power and spectral density do not remain constant, but rather fluctuate continuously. Still, despite the chaotic nature of the "behavior" of individual particles, the mean properties of a very large number of particles can be calculated with a high degree of accuracy. These were the methods used to determine the laws of thermal radiation.

One of the most important laws of thermal radiation is the law expressing the relationship between the spectral density of the radiation and its frequency, and the temperature of the radiator. This law can be written by the Planck radiation law

$$R_0 = \frac{2\pi f^3 h}{c^2\left[e^{\frac{hf}{KT}} - 1\right]} \quad W/Hz\cdot m^2 \qquad (1)$$

where

$h = 6.62 \times 10^{-34}$ J·s, is Planck's constant;

$c = 3 \times 10^5$ km/s, is the speed of propagation of electromagnetic waves;

$K = 1.38 \times 10^{-23}$ J·deg, is the Boltzmann constant;

T in °K is the absolute temperature of the radiator;

f in Hz is the frequency;

R_0 is the spectral density of the radiation, equal to the power radiated at frequency f in a 1 Hz band by 1 m^2 of the radiator.

Figure 1 shows the curves for radiation spectral density as a function of frequency and temperature. As may be seen from these curves, the radiant energy is unevenly distributed over the frequency spectrum. The spectral density is a maximum at definite frequencies, decreasing with increase and decrease in the frequency. /8

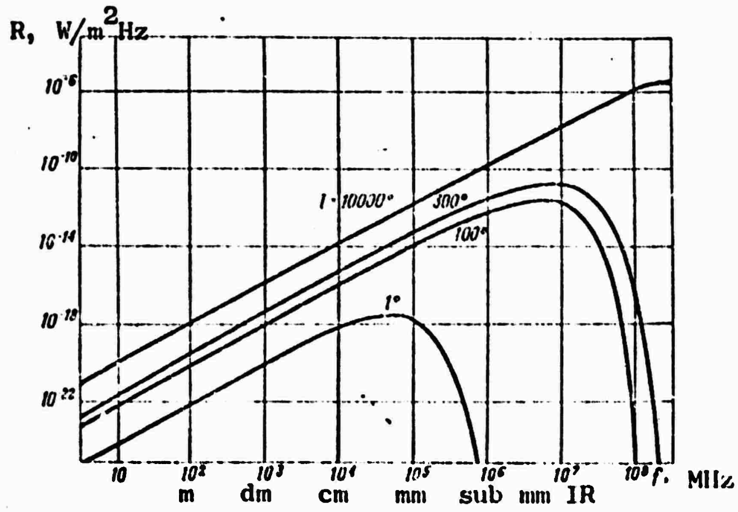


Figure 1. Spectral density of an ideal radiator as a function of frequency and temperature.

The frequency at which the spectral density is a maximum can be found from Wien's formula

$$f_m = 1.03 \times 10^5 T, \text{ MHz} \qquad (2)$$

What follows from the figure and Eq. (2) is that the spectral density maximum occurs in the band of optical and IR waves in the case of radiators with a temperature higher than ambient. The spectral density is less than the maximum by a factor of a thousand in the centimeter and millimeter bands.

The spectral density increases with increase in temperature at all frequencies, and what this means is that the total radiation power also increases. Summing spectral density on all frequencies, one obtains a formula for thermal radiation power over the entire band of electromagnetic waves /9

$$P = \sigma T^4 \quad W/m^2,$$

where

$$\sigma = 5.71 \times 10^{-8} \quad W/m^2 deg^4, \text{ is the Stefan constant.}$$

The summed power of the thermal radiation can be very great, but very little of it falls in the r-f region. The ideal radiator with an area of 1 m^2 will radiate power equal to 478 W at ambient temperature. The maximum spectral density will occur at a wavelength of 9.6 μ. The power radiated on wavelengths longer than one mm will be 8 mW in this case; that is, a little more than one-thousandth percent of the total power. The part of the power that can be perceived by a receiver is even less because modern receivers cannot simultaneously receive signals over the entire radio engineering band. Some of the power in the example cited that can be perceived by the receiver lies in the limits from 20 μW to 2-3 mW. The percentage of the power falling within the r-f band will decrease with increase in the temperature of the radiator because the spectral density in the IR and light wave region increases far and away more rapidly than the power spectral density in the radio engineering band. However, despite the relatively low power of thermal radio radiation, the latter can be picked up at greater distances than the more powerful IR and light radiation, thanks to highly sensitive modern radio receivers, and low attenuation of radio waves in the atmosphere.

It should be pointed out that Eq. (1) is valid only for the ideal radiator, the so-called absolute black body (ABB). The spectral density is lower for all real radiators than for the ABB heated to the same temperature. However the following formula can be used to calculate the spectral density for a real radiator from the known ABB spectral density

$$R = \alpha R_Q, \tag{3}$$

where

R is the spectral density for a real radiator;

$\alpha < 1$ is the coefficient of absorption, indicating the percentage of incident irradiation flux the particular real radiator absorbs if it irradiates on the same frequency as that on which the spectral density is determined. /10

Eq. (3) is the mathematical description of Kirchhoff's law establishing the relationship between the properties of radiation and absorption; the better the body absorbs radiation on some frequency, the greater will be the spectral density on the same frequency. Thus, the ideal radiation, the ABB, also is the ideal absorber.

Special Features of Thermal Radiation in the R-F Region

Thermal Radio Radiation as a Field of Noise Currents.

Let us consider the special features of thermal radiation in regions of radio waves (which, for purposes of simplicity we shall refer to simply as thermal radio radiation in what follows). First of all, we should point out that there is absolutely no need to use the cumbersome Planck formula to calculate spectral density in the centimeter and millimeter bands. In fact, the coefficient of the power of number e [see Eq. (1)] will become very small at frequencies in the r-f region. When f = 100,000 MHz (wavelength 3 mm) and T = 400°, $hf/kT \simeq 0.012$, for example. Using the known approximate equality

$$e^x \simeq 1 + x,$$

which is valid when $x \ll 1$, the Planck formula can be readily reduced to the form

$$R_0 = \frac{2\pi}{\lambda^2} kT, \tag{4}$$

where

λ is the wavelength of the radiation.

We have obtained the Rayleigh-Jeans formula, use of which will result in a quite accurate evaluation of the spectral density in the centimeter and millimeter bands for bodies with a temperature higher than 100°K.

As may be seen from this formula, the power of thermal radio radiation is directly proportional to the radiator temperature, and inversely proportional to the square of the wavelength. /11

Thus, it is more advantageous to use wavelengths in the millimeter and submillimeter regions than wavelengths in the centimeter and decimeter regions, in which radiation is much weaker, for the passive radar.

Let us now pause to examine one notable feature of Eq. (4). The fact is that the second factor on the right side (kT) is equal to the spectral density of the power of the thermal noise currents in the pure resistance

$$G_n = kT. \tag{5}$$

This is not coincidental. However, befo explaining it is necessary to pause briefly to consider certain properties of the thermal noise of pure resistances. This noise can be generated in any pure resistance, and its spectral density is constant from very low frequencies

to frequencies in the millimeter and submillimeter regions. Thermal noise currents are created in any nonideal conductor, and are the result of chaotic thermal motion of elementary charged particles. Noise such as this appears on PPI scopes in the form of characteristic unordered flickering points, and is reproduced at the outputs of radio broadcasting and communication receivers as a uniformly weak noise that can be heard quite well in the absence of the main transmission.

Thermal noise is generated only by pure resistance. Ideal condensers and induction coils do not generate noise currents. It is a known fact that pure resistance is capable of liberating heat when current flows; that is, electrical energy is converted into thermal energy. This means that inherent in pure resistance should be the reverse property, the capacity to partially convert thermal energy into electrical.

But any h-f current creates a field of electromagnetic radiation. At this point we are approaching the explanation of the resemblance between Eqs. (4) and (5). It is obvious that thermal radio radiation is the field of thermal noise currents flowing in the thickness of /12
the radiation body.

This can even be confirmed by the fact that the factor $2\pi/\lambda^2$, on the right-hand side of the Rayleigh-Jeans formula is equal to the factor in the formula for the radiation power for the elementary antenna, the length of which can be less than the radiation wavelength

$$P_{ant} = k_p(I^2_{ant}/\lambda^2)$$

where

P_{ant} is the power radiated by the antenna;

I is the antenna current

k_p is the proportionality factor.

A simplified model of thermal radio radiation therefore can be presented in the form of the summed radiation for a great many tiny elementary antennas supplied by the noise currents distributed over the volume of the radiator.

Since the cause of thermal radio radiation is SHF noise currents, the intensity of the radiation consequently should depend on the electrical properties of the substance of which the radiator is made, its conductivity, and permittivity. The conductivity of the substance will, to a considerable degree, determine its absorbing properties, and, as has been pointed out above, the better the body absorbs the energy of extraneous radiation, the better a thermal radiator it is.

High-quality dielectrics, for example, have very little conductivity, so their thermal radio radiation is slight. Antiradar coatings, which are

capable of almost completely absorbing UHF radiation incident upon them, have much greater conductivity (at ultrahigh frequencies), so the intensity of their thermal radio radiation is higher, as compared to all the other materials, and approaches the intensity of ABB radiation.

But the intensity of the thermal radio radiation depends on something other than the absorbing properties of the radiator material. Some of the radiation issuing from the depths of the radiator is reflected from its surface, and is once again converted into heat. This reflection is greater the greater the permittivity of the radiating material.

The magnitude of the reflection will, moreover, depend on the angle of incidence of the radiated waves, and on the type of polarization. These relationships can be written mathematically by the Fresnel formulas /13

$$\rho_h(\theta) = \left(\frac{\sin\theta - \sqrt{\varepsilon - \cos^2\theta}}{\sin\theta + \sqrt{\varepsilon - \cos^2\theta}}\right)^2; \qquad (6)$$

$$\rho_v(\theta) = \left(\frac{\varepsilon\sin\theta - \sqrt{\varepsilon - \cos^2\theta}}{\varepsilon\sin\theta + \sqrt{\varepsilon - \cos^2\theta}}\right)^2,$$

where

$\rho_h\theta$ is the coefficient of reflection of the component of the radiation with horizontal polarization;

$\rho_v\theta$ is the same, but for the component with vertical polarization;

ε is the permittivity for the radiator material;

θ is the angle of incidence of the radiation.

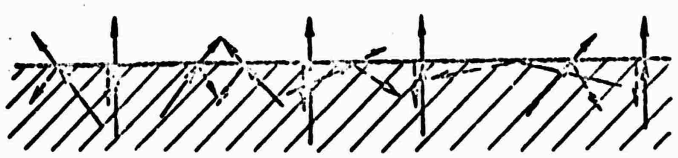


Figure 2. Reflection from the inner surface of a flat radiator.

The intensity of the thermal radio radiation departing the limits will differ in different directions, because of the dependency of the magnitude of the reflection on the angle of incidence and type of polarization, and will depend on the type of polarization (Figure 2). Accordingly, unique radiation patterns are formed at the radiator, and are different for the components of the radiation with vertical and horizontal polarizations.

As may be seen from Eq. (6), the coefficient of reflection $\rho_v(\theta)$ will equal zero at a predetermined angle of incidence, θ. The whole of the vertically polarized part of the radiation in this direction therefore will leave the radiator. The angle θ_v, at which $\rho_v(\theta) = 0$, is

called the Brewster angle, and its value can be found from the formula

$$\operatorname{ctg} \theta_v = \sqrt{\varepsilon}. \qquad (7)$$

Both coefficients, $\rho_h\theta$ and $\rho_v\theta$, increase with decrease in the angle of incidence. The coefficients equal unity when the angle of incidence is zero. The radiation in the direction parallel to the surface of the radiator therefore will be zero, and there is total internal reflection (Figure 3). /14

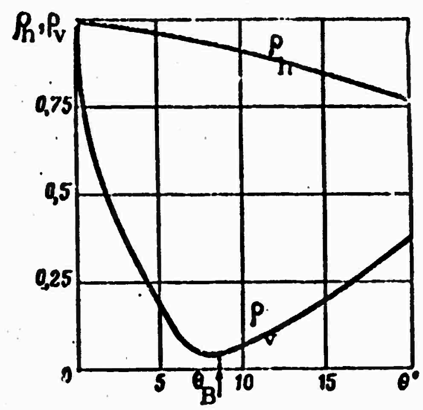


Figure 3. Coefficients of reflection as a function of the angle of incidence.

The dependence of radiation intensity on directions, as described, is valid for ideally flat radiators. The dependence of the level of radiation on the direction is smoothed in the case of radiators with uneven surfaces (Figure 4).

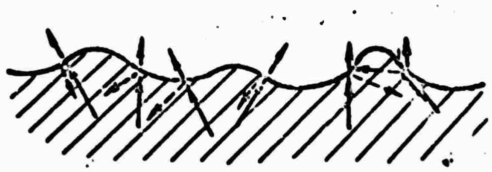


Figure 4. Reflection from the inner surface of a non-flat radiator.

Eq. (6) and Figure 2 are valid only for poorly conducting radiators with dielectrical properties. Good conducting radiations, metal ones, for example, have a coefficient of reflection close to unity, so the intensity of their own thermal radio radiation is very low.

Quantitative Characteristics of Thermal Radio Radiation /15

The spectral density of real bodies depends on two physical properties; the coefficient of absorption, α, and the absolute temperature, T. Operating with two different properties is not always convenient,

particularly when it is necessary to compare different radiating bodies (targets) with each other. This is why it has come to be accepted to use only one magnitude in passive radar, one equal to the product of the coefficient of absorption and the absolute temperature

$$T_b = \alpha T. \tag{8}$$

The magnitude T_b is called the radio brightness temperature of the particular radiator. It is equal to the absolute temperature of the ideal radiator generating radiation of the same spectral density as that of the given radiator. Although the wavelength does not enter into the expression for radio brightness temperature, as distinguished from the spectral density, as a practical matter the radio brightness temperatures of certain bodies and objects can depend on the wavelength because of the influence the wavelength has on the magnitude of the coefficient of absorption.

It already has been pointed out that objects that are good reflectors do not generate strong radiation of their own.

Thus, the radio brightness temperature of metal objects and coatings does not exceed 10-20°K. Nevertheless, metal objects can intensively reradiate (reflect) thermal radio radiation incident upon them from extended (background) sources (the terrestrial surface, clouds). The summed spectral density of own and reflected radiation can be written in the form

$$R_t = \frac{2\pi}{\lambda^2} (\alpha T + \rho T_i) = \frac{2\pi}{\lambda 2} T_a; \tag{9}$$

$$T_a = \alpha T + \rho T_a,$$

where

ρ is the body's reflectivity;

T_i is the radio brightness temperature of the intensifying radiation;

T_a is the so-called apparent temperature of the radiator.

Determined similarly to the radio brightness temperature, the apparent temperature is equal to the absolute temperature of an ideal radiator creating eigenradiation equal to the summed radiation for the specified real radiator. /16

But as distinguished from the radio brightness temperature, the apparent temperature can be greater than the radiator's absolute temperature. It is handy to use the values of the radio brightness and apparent temperatures when comparing different real radiators.

Calculation of the magnitude of the power radiated by a particular object is of great interest. The power of the thermal radio radiation

depends on the apparent temperature and on the area of the object, its shape, smoothness of the object's surface, and a number of other factors difficult to take into consideration. However, these factors can be ignored in the case of objects with a simple configuration. The expression for radiation power then can be written in the following form

$$P_r \simeq \frac{2\pi}{\lambda^2} kT_a S_t \Delta f, \qquad (10)$$

where

S_t is the target area;

Δf is the frequency band in which the radiated power is being evaluated.

Everything thus far discussed has concerned the energy characteristics of radiation; brightness temperature, apparent temperature, power. But knowledge of just these characteristics is not enough to evaluate the potentials for detecting thermal radio radiation. What still must be known in order to do so is required "antenna patterns" for the thermal radio radiators, and required antenna polarization to receive the radiation.

As distinguished from the patterns for radar reradiation, which, for the majority of targets, have a jagged lobed structure, the patterns of thermal radio radiation are much more uniform. This is quite understandable because the radiation from the target is made up of radiations from individual sections that have absolutely no dependence on each other. There can be no nulls in the patterns of own thermal radio radiation, in principle, and it can be taken as a first approximation that the radio brightness temperature of targets with uncomplicated shapes made of /17
a homogeneous material does not depend on the bearing. This is the fact of the matter in the case of area ("background") radiators with unevennesses of surface that are small compared to the wavelength ("rough" radiators). If the surface of the radiator is absolutely smooth, or if the height of the unevenness is very much greater than the wavelength, the radiation factor, and the magnitudes of the radio brightness and apparent temperatures as well, will depend on the bearing on which the reflector "is viewed" by the passive radar [see Eq. (6)].

Thermal radio radiation from natural and artificial objects. Real thermal radio radiators (artificial and natural) often have properties that differ greatly from those of the ideal radiator, the ABB. The apparent temperature of real radiators therefore can change with change in wavelength and type of polarization.

Moreover, the apparent temperature of objects also can depend on the bearing on which such objects are observed. Finally, the time of day, time of year, and meteorological conditions, particularly the degree of moisture of the surface of the object, will have an influence on the magnitude of the apparent temperature.

Metal objects are very poor radiators, so their apparent temperatures will, in the main, be determined by the brightness temperature of the intensifying background. Figure 5 shows the curves for the

apparent temperature of a metal plate as a function of the angle at which the plate is observed. The curves were constructed from results of experimental study conducted in the 4 mm band. As may be seen from the curves, the radio brightness temperature of the metal plate is no more than 10-18°K over the entire band of angles of observation, with the polished surface radiating more weakly than the unpolished. Nor is there any increase in the apparent temperature when a thin coat of paint is applied to the plate. The curves in Figure 5 lead to the conclusion that a metal plate is a unique "mirror" in which a "hotter" sky can be /18
reflected. Experimental data cited in foreign literature suggest that the apparent temperature of metal objects at ground level is very much lower on a wavelength of 8 mm than in the 4 mm band, and does not exceed 50°K. This can be explained by the lower radio brightness temperature of the sky in the 8 mm band. For this reason, the apparent temperature of metal ground objects will be even lower in the centimeter band. We should point out that the apparent temperature of metal objects has virtually no dependence on their physical temperature, so there is no way for passive radars to distinguish heated metal objects from cold ones, something that can be done with IR equipment, for example.

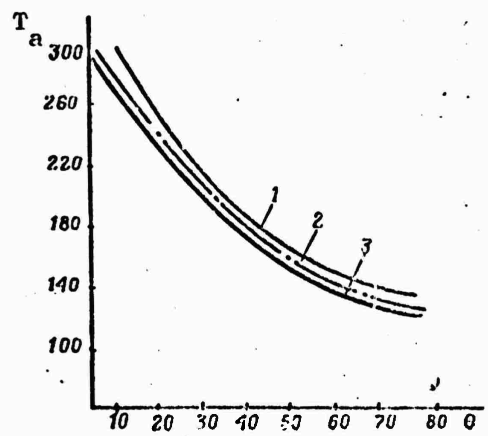


Figure 5. Apparent temperature of a metal plate as a function of sighting angle (wavelength 4 mm). 1 - unpolished metal; 2 - polished metal; 3 - sky.

The apparent temperatures of buildings, and various artificial structures made of nonmetallic building materials, are considerably higher (230 to 250°K). The majority of these materials are dielectrics with high losses, so their radiation factor is comparatively great. /19
Other countries also are studying radiation from asphalt and concrete coatings, the presence of which is a characteristic feature of many military, industrial, and transportation objects (roads, runways, missile positions, and the like). These coatings are flat, relatively smooth surfaces, so their apparent temperature is greatly dependent on the angle of observation. Figure 6a shows curves of apparent temperature of asphalt as a function of the angle of observation, θ, on different wavelengths. As may be seen from these curves, the apparent temper- /20
ature of asphalt can take values from 100° to 300°K. The apparent temperature of concrete can vary in the limits 260°-290°K.

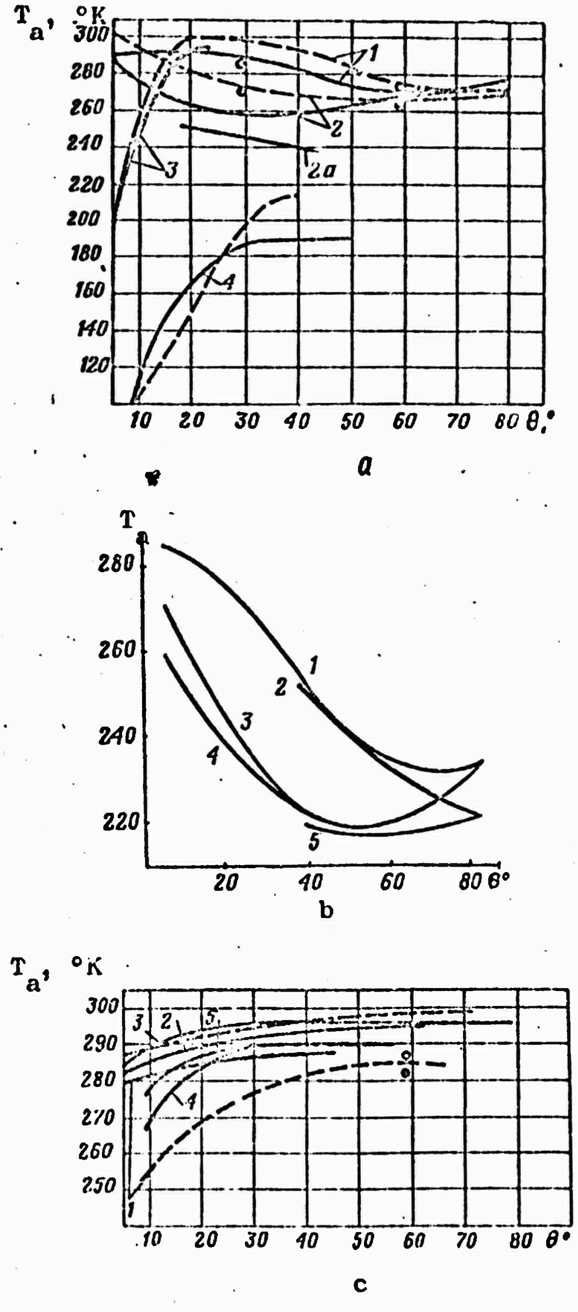


Figure 6. Apparent temperatures of asphalt, a water surface, and a grassy cover as a function of the sighting angle and wavelength. (a) asphalt: 1 - λ=0.4 cm, vertical polarization; 2 - λ=0.4 cm, horizontal polarization; 2a - same, wet asphalt; 3 - λ=3.2 cm, horizontal polarization; 4 - λ=3.2 cm, vertical polarization; . - λ=0.8 cm, horizontal polarization; ° - λ=0.8 cm, vertical polarization; --- theory; ___ experiment;

(b) water, vertical polarization; 1 - wavelength 15-20 cm; 2 - smooth surface, horizontal polarization; 3 - wavelengths 5-10 cm; 4 - wavelengths 15-20 cm; 5 - smooth surface; (c) grassy cover, wavelength 4 mm; 1 - horizontal polarization; 2 - vertical polarization; 3 - vertical polarization (forest); 4 - horizontal polarization, wavelength 3.2 cm; 5 - vertical polarization, wavelength 3.2 cm; ° - vertical polarization, wavelength 0.8 cm; . - horizontal polarization, wavelength 0.8 cm; ___ experiment; ---theory.

An important condition, and one needed to detect an object from its thermal radio radiation, is a difference between the apparent temperature of the object and the apparent temperature of the surface, of the background against which that object is located. This is why research in the thermal radio radiation of typical backgrounds of ground and water surfaces, the atmosphere, clouds, and the different types of atmospheric precipitation has been, and is being conducted. It has been established, moreover, that the apparent temperature of different sections of the earth's surface are very little dependent on wavelength and type of polarization. Curves of apparent temperature of grassy covers, forests, and agricultural crops as a function of the wavelength, and of the /21
angle of observation, are drawn in Figure 6c. As may be seen from these curves, the apparent temperature of sections of the earth's surface overgrown by forests, by crops, and by grass is not too different. Thus, forests and grassy covers will radiate in the centimeter and millimeter bands in almost the same way as will the ideal radiator, the absolute black body. Radiation from surface radiators is quite heavily dependent on how wet their surfaces are. The apparent temperature of asphalt and concrete coatings in rainy weather will increase by 3° to 7°, for example. Since the physical temperature of the earth's surface changes with change in time of year, and over any 24 hour period, so too will the apparent temperature of the terrestrial surface change. The maximum apparent temperature of a winter forest in the 10 cm band, for example, will change as the day wears on, from 227° (0700 hours) to 243° (1600 hours). The apparent temperature of water surfaces (rivers, lakes, seas) is heavily dependent on the angle of observation, type of polarization, and surface conditions. Figure 6b shows curves of the apparent temperature of lake (fresh) water as a function of the angle of observation and type of polarization.

Surface waves will help increase the water's apparent temperature because the foamy tops of the crests have a higher radiation factor than the water proper. Interestingly enough, the apparent temperature of ice is several tens of degrees higher than the water temperature. This can be explained by the high radiation factor for ice.

Absorbent coatings can be used to mask metal objects from detection by radar, as we know. But, as should be obvious, these coatings will not mask thermal radio radiation because they themselves are good thermal radio radiators.

Rocket engine tails are powerful sources of thermal radio radiation. The high temperature generated by a burning rocket engine will cause intensive ionization of the molecules of the gases that form. The free

electrons that form during ionization cause a sharp increase in the electrical conductivity of the gases. The tail thus can be considered a conducting body with heavy electrical losses, and as a result the tail absorption factor is quite high (0.5-0.7) in the centimeter and millimeter bands. The tail temperature reaches 3,000° to 4,000°K. So it is obvious that the tail radio brightness temperature is 1,500°-2,800°K; that is, higher than that of ground objects by a factor of 10, roughly speaking [4]. /22

Electron density drops rapidly with decrease in ambient air pressure, and the absorption factor decreases as a result. The absorption factor also can decrease with shortening of the wavelength. And the tail radio brightness temperature will change in proportion to the absorption factor.

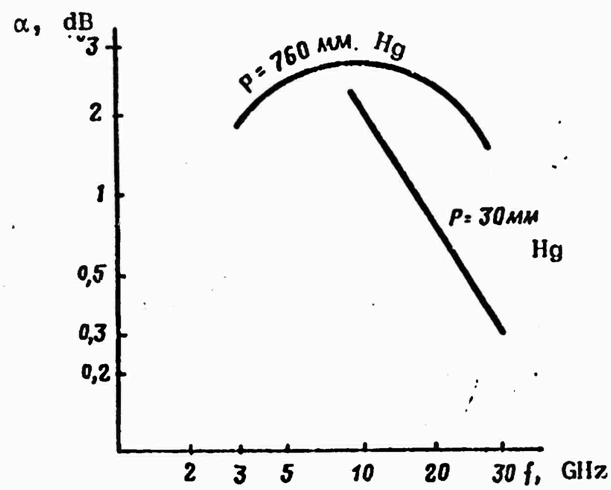


Figure 7. Rocket engine tail absorption factor as a function of frequency and atmospheric pressure.

Figure 7 shows the absorption factor as a function of flight altitude and wavelength. Soviet scientists A. Ye. Basharinov and V. M. Polyakov have made a significant contribution to research in the thermal radio radiation taking place when different fuels are burned. They have shown that radiation from the flames of burning fuel occurs as a result of the ionization of the gases, of the products of combustion, as well as because there are a great many particles of unburned fuel in the flame. Each such particle is a thermal radio radiator. /23

Sizes of radiating particles can differ, from thousandths to tenths of a millimeter. Radiation on wavelengths that are approximately the same will be the most intense; the particles are in resonance, as it were. In this case, therefore, the apparent temperature will increase with shortening of the wavelength.

Figure 8 shows the curves for the radiation factor for the flame of burning solid fuel as a function of the wavelength, plotted from experimental data obtained by A. Ye. Basharinov and V. M. Polyakov. Note that the most intense radiation from the flame is in the millimeter band.

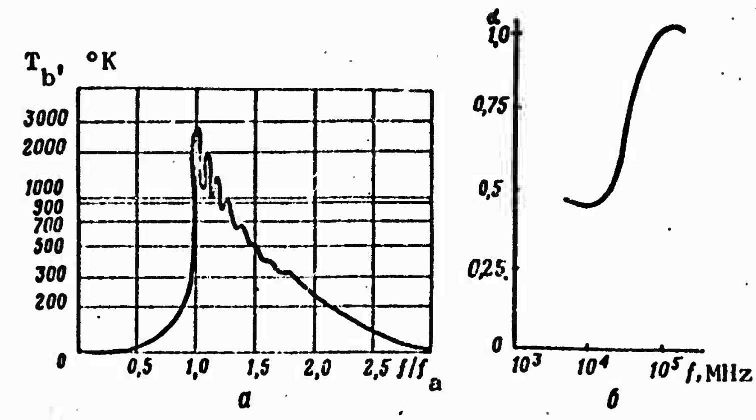


Figure 8. Relationships: (a) apparent temperature as a function of the frequency; (b) flame radiation factor as a function of the wavelength.

Intense thermal radio radiation is created by plasma forming during the flight of different objects in the atmosphere at speeds several times in excess of the speed of sound. The surface of the body, as well as the contiguous air layer, are heated to several thousand degrees and the air in the layer containing the particles of the evaporating skin of the body is almost completely ionized. And as we already know, a heated and highly ionized gas is a good thermal radio radiator. /24

The radio brightness temperature of plasma can reach several tens of thousands of degrees. Its magnitude will depend in quite a complex fashion on temperature, pressure, and chemical composition of the skin, density of the ambient air, and on a number of other factors. Figure 8a shows a curve for radio brightness temperature of a 4 cm thick plasma layer with a physical temperature of 5,000°K as a function of frequency [4].

It is the opinion of American experts that approximately this sort of plasma layer is what forms around the heads of rockets sent up to great heights in the dense layers of the atmosphere. The unique shape of the curve draws one's attention as it drops sharply from some frequency, f_a. This phenomenon can be explained by the strong dependence of the conductivity and the permittivity of the plasma on the frequency. Plasma conductivity is very high at frequencies below f_a, but decreases with increase in frequency. The wavy nature of the curve can be explained by the repeated reflection of radiation inside the plasma layer. The critical f_a will depend primarily on the spatial density of the electrons (the number of electrons/cm³ of plasma) in accordance with the formula

$$f_a \approx 0.009\sqrt{n}\ , \text{ MHz.} \qquad (11)$$

Density of electrons in the plasma in turn will depend on flight speed and altitude, and particularly on the chemical composition of the body's skin.

So-called betatron radiation is added to the plasma's thermal radiation when a magnetic field acts on the plasma. Physically, this

radiation is associated with the curvature of the trajectories of the electrons in the magnetic field. Curvature of the trajectory causes lateral (centripetal) acceleration, and the charged particles radiate electromagnetic energy as they are accelerated and retarded.

Betatron radiation takes place on a single frequency that depends solely on the magnetic field intensity

$$f \simeq 2.8I, \text{ MHz}, \tag{12}$$

where

I is the magnetic field intensity, oersteds.

Betatron radiation will take place in the centimeter band when /25 the magnetic field intensity is in the thousands of oersteds, and in the millimeter band when in the tens of thousands of oersteds. Betatron radiation is not, strictly speaking, thermal radio radiation because it is not associated with thermal noise currents and can occur when electron streams, however created, are magnetized. Betatron radiation from plasma, however, occurs because of the plasma's thermal energy, characteristic as well of conventional thermal radio radiation.

Radio radiation from the atmosphere, Sun and Moon. The water vapor and oxygen always present in the earth's atmosphere is what creates the major part of the thermal radio radiation in that atmosphere. Clouds and precipitation are sources of very intense thermal radio radiation in the millimeter band. The radio brightness temperature of the sky depends on the angle of observation. The closer to the horizon one tilts the line of sight, the thicker the layer of atmosphere this line will penetrate. The maximum radio brightness temperature clearly will be found at the zenith, the minimum near the horizon. Figure 9 shows curves for the radio brightness temperature of the atmosphere as a function of the angle of observation and the frequency. As may be seen, the maximum is at 2.4 GHz, which correspond to resonance absorption in water vapors. The sky's radio brightness temperature decreases with increase in altitude because the atmosphere's absorption factor is greater the greater the atmospheric density.

Rain has the highest thermal radio radiation of all the meteorological precipitations. The heavier the rain, the higher its radio brightness temperature. Figure 10 shows curves for radio brightness temperature of rain areas as a function of wavelength and rain intensity. Note that the rain area radio brightness temperature is very much higher in the millimeter band than in the centimeter band. More detailed information on atmospheric and precipitation radio radiation can be found in L. T. Tuchkov's book Natural Noise Radio Radiations in Radio Channels.

Radiation from the sky includes cosmic radio radiation, as well as radiation from the atmosphere. Radio astronomers are concerned with cosmic radiation study, but radiation created by the Sun, the Moon, and certain of the planets and stars, is of interest from the point of view of passive radar use.

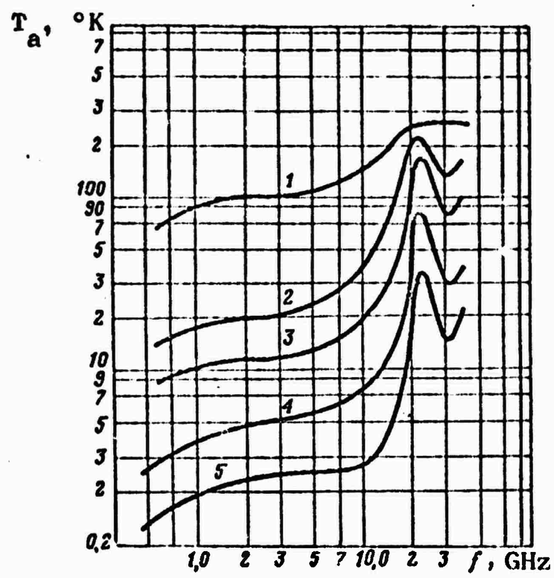


Figure 9. Apparent temperature of the atmosphere as a function of the angle of observation and the frequency. Values of angles: 1 - 0°; 2 - 5°; 3 - 10°; 4 - 30°; 5 - 90°. /26

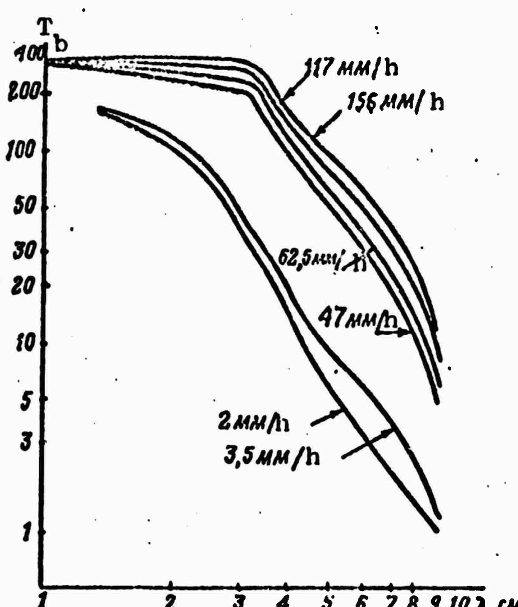


Figure 10. Apparent temperature of the atmosphere as a function of the wavelength and intensity of precipitation. /27

Radio radiation from the Sun and Moon has been elucidated in much special literature, so we here will simply present the apparent temperature of the Sun and planets as a function of the frequency (Figure 11). Note that the most powerful source of radio radiation is the Sun, the radio brightness temperature of which is 7000°-8000°K in the millimeter band, and 30000°-60000° in the centimeter band. The upper curve for solar radio radiation corresponds to the years of maximum solar activity, the lower to the "quiet" sun.

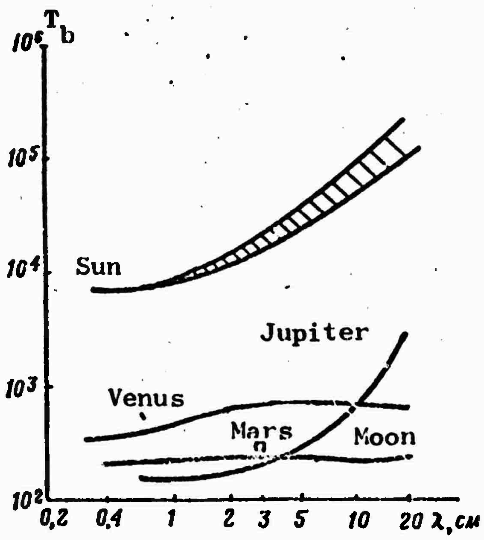


Figure 11. Apparent temperatures of the Sun and planets.

Radio radiation is created far out in space, but this radiation is so slight in the centimeter and millimeter bands that there is no need to consider it here. /28

In concluding this chapter, we should point out that thermal radio radiation is certainly not the only form of natural electromagnetic radiation suitable for passive radar purposes. We have already considered, for example, the betatron radiation from plasma, which certainly cannot be included with "pure" thermal radio radiation. Nor are other forms of natural electromagnetic radiation, including radiation occurring during static discharges of atmospheric electricity, and spark formation at current carrying contacts, considered to be thermal radio radiation.

It is entirely possible that other forms of natural electromagnetic radiation suitable for use in passive radar work will be discovered.

2. Reception of Thermal Radio Radiation /29

Thermal Radio Signals. Signal Characteristics.

If an antenna is placed in a thermal radio radiation field, a noiselike voltage will appear at its terminals. It is not entirely correct to call this voltage a thermal radio signal because its frequency spectrum is very much wider than the bandwidths of modern receivers.

A receiver connected to the antenna in this particular case will reproduce what is a comparatively small region of the input voltage spectrum. We shall refer to that part of the input voltage that corresponds to this region as the thermal radio signal in what follows.

This definition makes it apparent that the characteristics of the thermal radio signal, as distinguished from radar signals, will depend on receiver characteristics.

Thus, the power of the thermal radio signal is directly proportional to the width of the receiver's bandwidth at high (or intermediate) frequency. This is precisely why efforts are made to use receivers in passive radars that have very wide bandwidths, those in the hundreds, thousands, and even tens of thousands of megahertz. The power of thermal radio signals then can be amplified and can, in some cases, be as high as 10^{-10} W. A signal of this strength is characteristic of passive radars used to scan the terrestrial surface, for example. Let us, for purposes of comparison, recall that the strength of signals incoming to foreign long-range radars used to detect air and space objects often is a maximum /30 of 10^{-20} W. Special highly-sensitive receivers capable of detecting very weak signals now have been developed for passive radar sets [11].

It often is convenient to express signal intensity in units of spectral density, rather than in units of power, when making calculations. This evaluation is more objective because, as distinguished from the power, the spectral density does not depend on receiver bandwidth. The spectral density of thermal radio signals is expressed in temperature units, as in the case of calculations of radiation spectral density.

Spectral density and signal power are associated by the following relationships

$$P_s = kT_s\Delta f,$$

$$T_s = P_s/k\Delta f.$$

The magnitude kT_s is the signal power spectral density. T_s is called the signal temperature. It is taken to be equal to the physical temperature of the pure resistance creating a noise voltage with a spectral

density equal to the spectral density of the power for the given signal. The term "antenna temperature" often is used in this context. But here what is meant is the temperature of the signal right at the antenna output. But what must be emphasized is that the spectral density of some thermal radio signals depends on frequency, and this is different from the noises generated by pure resistances. The temperature of signals from small objects will increase with increase in frequency, for example. This phenomenon can be used to select signals and to identify their sources. The width of the band of frequencies covered by the signal is a very important signal characteristic because signal power, as well as the accuracy with which the time of arrival of signals at multichannel passive radar systems is measured, depend on this width.

The length of thermal radio signals depends on the time the target remains within the main lobe of the antenna pattern. Signal length can vary from units of a millisecond to several minutes, depending on the scanning mode and the nature of the target. Signal energy is proportional to signal length, so the possibility that the signal will be detected improves with increase in signal length, as does the accuracy with which signal amplitude can be measured. /31

An increase in the signal length will increase the accuracy with which the Doppler shift in signal frequency can be measured in two-channel passive radars.

Special features of the reception of thermal radio signals. Radiometer operating principles. As we know, the chief difficulty in the reception of weak signals results from the need to separate them from the background of receiver noises generated in the first stages of the receiver. Receiver noise in communication and radar receivers is reduced by using frequency selection and time gating, so that the signal power at the output of the receiver's h-f section will be well above noise power. But neither of these can be used to receive thermal radio signals because the signals themselves are similar to noise in nature. This is why thermal radio signal receivers are designed to be accurate noise level measurers, and hence such receivers have come to be called radiometers.

The simplest radiometer (Figure 12) consists of a high-frequency amplifier (HFA), a detector, and a low-pass ripple filter (LPF); that is, it is a conventional direct amplification receiver. The HFA is needed to weaken the influence of detector noise, as well as noise generated in succeeding stages, so its own noise should be low. Efforts should be made to make the HFA bandwidth as wide as possible in order to increase the power of the thermal radio signal. The amplifier thermal radio signal is fed from the output of the HFA into the square-law detector. The detector's output voltage has a constant component, but it also has an intense noise component that "masks" the separated useful signal. The LPF which, in its simplest form, is an integrating RC-filter, suppresses this noise. /32

Figure 12. Functional diagram of the simplest radiometer.

The main feature of the simplest radiometer is its capacity to reliably receive signals, the power of which is very much lower than the power of own noise. This capacity depends on a combination of a broad h-f bandpass and a narrow bandpass for the LPF installed after the detector. This combination is characteristic of the majority of modern radiometers.

Let us consider the passage of signal and noise through the stages of the simplest radiometer. The power of signal and noise at the radiometer input will be

$$P_s = kT_s\Delta f;$$

$$P_n = kT_n\Delta f = k(N - 1)T_s\Delta f,$$

where

$T_n = (N - 1)T_s$ is the HFA noise temperature;

$T_s = 300°K$ is the standard temperature;

N is the HFA noise factor.

The signal/noise power ratio at the radiometer input, q_{in}, will equal

$$q_{in} = P_s/P_n = T_s/T_n. \qquad (13)$$

One can be readily persuaded that the signal/noise power ratio (let us, for brevity's sake, simply call this the s/n ratio) will not change after h-f amplification

$$q_{HFA} = P_sK_{HFA}/P_nK_{HFA} = T_s/T_n = q_{in} \qquad (14)$$

What this means, from a physical standpoint, is that the HFA amplifies internal noise and noise-like signals identically. Even when HFA with low noise levels are used their noise as a rule is considerably greater than the signal temperature, so that the s/n ratio is less than unity at the detector input. But the noise signal is suppressed in the detector, /33
and the ratio of the power of the detected signal (the constant component) to the power of the noise at the detector output will equal

$$q_d \approx q_{HFA}^2 = q_{in}^2 = (T_s/T_n)^2. \qquad (15)$$

Now let us turn our attention to the fact that while the noise at the detector output retains its broadband nature, its spectrum will now be part of the l-f region (Figure 13).

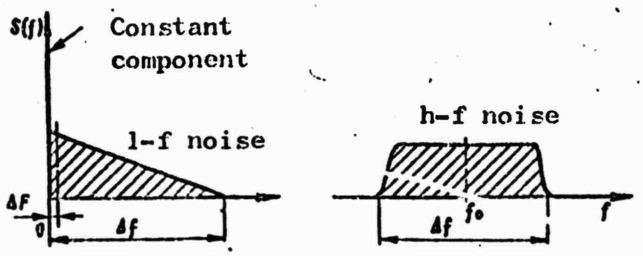


Figure 13. Influence of h-f and l-f passband widths on noise level at the radiometer output.

Actually, the h-f noise prior to detection can be considered the result of modulation of the carrier by the l-f noise with a spectrum in the limits 0 - Δf. The result of the detection is the separation of this "modulating" noise. The LPF, which has a passband ΔF, considerably less than the Δf for the HFA, will only pass a small part of this noise, but will not interfere with the passage of the useful constant component. As may be seen from the figure, the noise power at the LPF output is less than the noise power at the LPF input by a factor $\Delta f/\Delta F$. Accordingly, the output s/n ratio will equal

$$q_{out} = q_d (\Delta f/\Delta F) \simeq (T_s/T_n)^2 (\Delta f/\Delta F) = q_{in}^2(\Delta f/\Delta F). \quad (16)$$

The $\Delta f/\Delta F$ ratio in modern radiometers is 10^7 to 10^9, so a large s/n output ratio is obtained for an input s/n ratio of less than unity. Let /34
us look at a practical example. Let $T_s = 1°$, $T_n = 100°$, $\Delta f = 100$ MHz, and $\Delta F = 1$ Hz. Eq. (16) will yield $q_{out} = 10{,}000$. But an infinite increase in the output s/n ratio because of compression of the LPF passband is impossible because of the limited length of the thermal radio signal. As we know, the result of the detection of a signal such as this is the formation of a d-c pulse, the spectrum of which covers the band of frequencies from 0 to F_s, the width of which is inversely proportional to the signal length

$$\Delta F_s = F_s \simeq 1/t_s.$$

Reducing the LPF passband to a magnitude less than ΔF_s will result in suppressing the signal along with the noise; that is, there will be no increase in the s/n ratio. So the maximum attainable s/n ratio will be equal to

$$q_{out} \simeq (T_s/T_n)^2 \Delta f t_s. \quad (17)$$

We should point out that the formula is valid only for an idealized simplest radiometer in which there is no signal loss in the section from

the antenna output to the receiver input, where the frequency curve for the HFA is rectangular, the detector is square-law, and the LPF is ideally matched to the length and shape of the incoming signal envelope. This is why the output s/n ratio is less than in the case of the idealized radiometer by a factor of from 5 to 50, given the same T_s, T_n, Δf, and t_s values.

The principal technical characteristic of any radiometer is sensitivity, that is, the capacity of the radiometer to receive weak thermal radio signals. The sensitivity of a radiometer is numerically equal to the temperature of a signal at the radiometer input that will yield a s/n ratio of 1 at the output. The formula for the sensitivity of the simplest radiometer is readily obtained from Eq. (16) by equating its right-hand side to unity

$$\delta T = T_n / \sqrt{\Delta f t_s}. \tag{18}$$

The less sensitivity δT, the more sensitive the radiometer. The sensitivity of the radiometer cited in the above example is 0.01°. /35

This definition of sensitivity is provided in order to simplify its practical measurement. Sensitivity is equal to the root-mean-square of random oscillations of the needle of the output meter (or recorder), expressed in temperature units. Therefore, the sensitivity can be approximated, even "by eye," once a certain skill has been acquired. Sensitivity often is converted to signal length, equal to 1 sec, for convenience in comparing different radiometers. Sensitivity obtained in this manner is called normalized.

Passive radar techniques often require that a comparison be made between two, or several, thermal radio signals. Additional information, such as target movement and target angular coordinates, something that is impossible when the simplest radiometer is used, can be obtained from the signals. Radiometers designed for the combined reception of two thermal radio signals are called correlation radiometers (Figure 14a). As may be seen from the figure, the principal difference between the correlation radiometer and the simplest radiometer is the presence of two HFA and signal multipliers, rather than a square-law detector. The correlation radiometer functions in the same manner as the simplest radiometer if the identical thermal radio signal is supplied to the HFA input because the multiplication of two identical signals is the equivalent of square-law detection of either of the signals. But if one of the input signals lags the other, the output voltage will be reduced and will equal zero when the relative delay in the signals, t_d, is equal to one-fourth of the period of the signal's mean frequency. The output voltage will change sign with further increase in the delay, and will increase right up to the time when t_d is equal to one-half the period of the mean frequency. It then will decrease, pass through zero, become positive, and so on. In other words, the output voltage will periodically become positive and negative with continuous change in t_d. This type of change in the voltage can be explained by the fact that the multiplication

curcuit is, in essence, a phase detector, and the difference in the signal phases is proportional to their time delay. /36

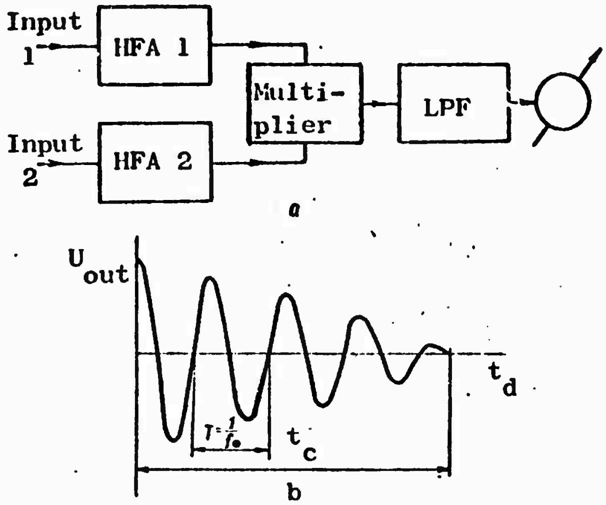


Figure 14. Correlation radiometer. (a) - block diagram. (b) - output voltage as a function of delay time.

Figure 14b is the output voltage as a function of t_d. Noteworthy is the fact that the maxima decrease steadily with increase in t_d. The output voltage, or more exactly, its constant component, will equal zero when $t_d \simeq 1/\Delta f$. This is related to the noise-like nature of the input signal. Its frequency changes continuously and randomly, so the segments of the signal over the interval longer than $1/\Delta f$ will have a distinguishing frequency, while signals with different frequencies cannot develop d-c at the phase detector output.

We should point out, in passing, that the formula $U_{out} = f(t_d)$, shown as a curve in Figure 14b, is none other than the autocorrelation function of the signal, an important characteristic. The interval $t_c \simeq 1/\Delta f$, which corresponds to the decay in the autocorrelation function to a predetermined very small value, is called the correlation interval. What follows from the foregoing is that the correlation radiometer will not record /37 identical signals shifted in time longer than t_c. Nor will thermal radio signals incoming simultaneously from different sources be recorded because their instantaneous frequencies change according to different laws.

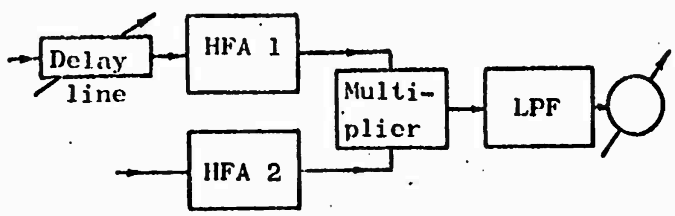


Figure 15. Measurement of relative signal lag time.

A delay line with variable delay time (Figure 15) can be used to measure the relative signal lag time for signals arriving at radiometer inputs 1 and 2. Signal delay time in the line changes until the radiometer output voltage is a maximum, whereupon the signal delay time in the line will be equal to the relative signal lag time.

Signal frequency shift also can be measured by the correlation radiometer. The need for so doing could arise, for example, when thermal radio signals from moving targets are received by antennas. The signals at the outputs of the antennas have different Doppler shifts, and this difference in shifts, characterizing target speed and range, can be measured by a correlation radiometer. In this case the LPF at the radiometer output is replaced by l-f bandpass filters, the passbands of which cover the possible region of changes in the different Doppler shift.

The formulas used for the simplest radiometer can be used to approximate the s/n ratio, and the sensitivity of the correlation radiometer. However, consideration must be given to the fact that noise power in the correlation radiometer is twice what it is in the simplest radiometer. Therefore, the output s/n ratio is less by a factor of 4, and the sensi- /38
tivity is lower by a factor of 2, as compared to the simplest radiometer when the correlation radiometer is used in the single-channel mode.

<u>Functional diagrams of modern radiometers</u>. The simplest radiometer has two major shortcomings. First of all, a voltage proportional to the temperature of own noise will appear across the radiometer output when there is no signal. And because this temperature can be many times higher than the signal temperature, detection, and particularly measurement, of signal temperature is very difficult.

Second, and even more serious, is the fact that the constant component of the detected own noise voltage is modulated by these changes because of the slow random changes (drift) in the gain in the h-f stages. The additional random noise has a spectrum concentrated in the region of very low frequencies, and therefore passes through the l-f filter unimpeded. This noise cannot be reduced, even if the h-f passband is expanded. The first of these shortcomings can be overcome by introducing bias voltage into the radiometer's output circuit that is equal in magnitude, and opposite in sign, to the voltage generated by the rectified own noise. The voltages will cancel each other, and the output meter will read zero, if there is no signal. The simplest radiometer thus modified is called a <u>compensated</u> radiometer.

The compensated radiometer, because of its simplicity, has enjoyed some use, but like the simplest radiometer, is subject to the influence of drift in gain. It is very difficult to overcome this influence because even the slightest fluctuation in gain will result in a sharp deterioration in sensitivity. For example, even a 0.1% fluctuation in the gain will cause the output meter needle to deflect as if a 1° signal were present at a noise temperature of 1000°K and the radiometer sensitivity is unacceptably reduced as a result.

Development of receivers with superstable gain is a serious technical task. Moreover, such receivers are complicated and expensive. It is particularly difficult to ensure high gain stability when the radiometer is installed in aircraft and rockets where mechanical vibration will effect the gain, and so too will random fluctuations in the voltage of the installed power supplies. It would, therefore, be highly desirable to modify radiometer circuitry to avoid "confusing" the signal by surges when gain fluctuations occur. There are two ways this can be done. One is to "color" the signal arriving at the receiver input. The other is to use multichannel receivers. Let us consider the first of these. /39

Random changes in gain have one very characteristic property; they are very slow, as a rule. Therefore, if the signal is modulated by a sufficiently high frequency before it reaches the receiver input, the signal will be separated at the receiver output almost uncluttered by fluctuations in the gain. Herein is the operating principle of the modulated radiometer, one of the most widely used types today (Figure 16).

As may be seen from the figure, a narrow-band LFA, tuned to the modulation frequency, is installed in the receiver detector output. The LFA amplifies the modulated signal and heavily suppresses the interference caused by fluctuations in the gain because its spectrum does not coincide with the LFA passband. The synchronous detector, in combination with the l-f filter, too has a selective effect with respect to the signal, and this eliminates the modulation from the signal.

Thus, if the modulation occurs at a sufficiently high frequency, the modulated radiometer, as distinguished from the simplest and compensated types, will not be subject to the harmful influence of fluctuations in receiver gain.

The modulated radiometer does have certain drawbacks, however. Its sensitivity is not as high as that of the simplest and compensated radiometers because part of the signal energy is expended during modulation. It has been demonstrated, at least theoretically, that what is needed in order to obtain the greatest sensitivity is a meander to /40
modulate the signal; that is rectangular pulses with the same duty ratio.
At the same time, half the signal energy will be lost in the modulator, /41
so the sensitivity of the modulated radiometer will equal

$$\Delta T_m = 2T_n \left(1/\sqrt{\Delta f \tau_s}\right) = 2\Delta T, \quad (19)$$

that is, it will be lower than that of the simplest radiometer by a factor of 2.

Like the simplest radiometer, the modulated radiometer does not read zero when there is no signal. This can be explained by the special features of modulator operation. The fact is that when the modulator is in the cutoff state, that is, the signal is completely absorbed, it will generate noise with a temperature equal to its physical temperature. Thus, the meter at the radiometer output will read the temperature difference $T_m - T_s$, where T_m is the physical temperature of the modulator, rather than the signal temperature. This drawback can be eliminated by

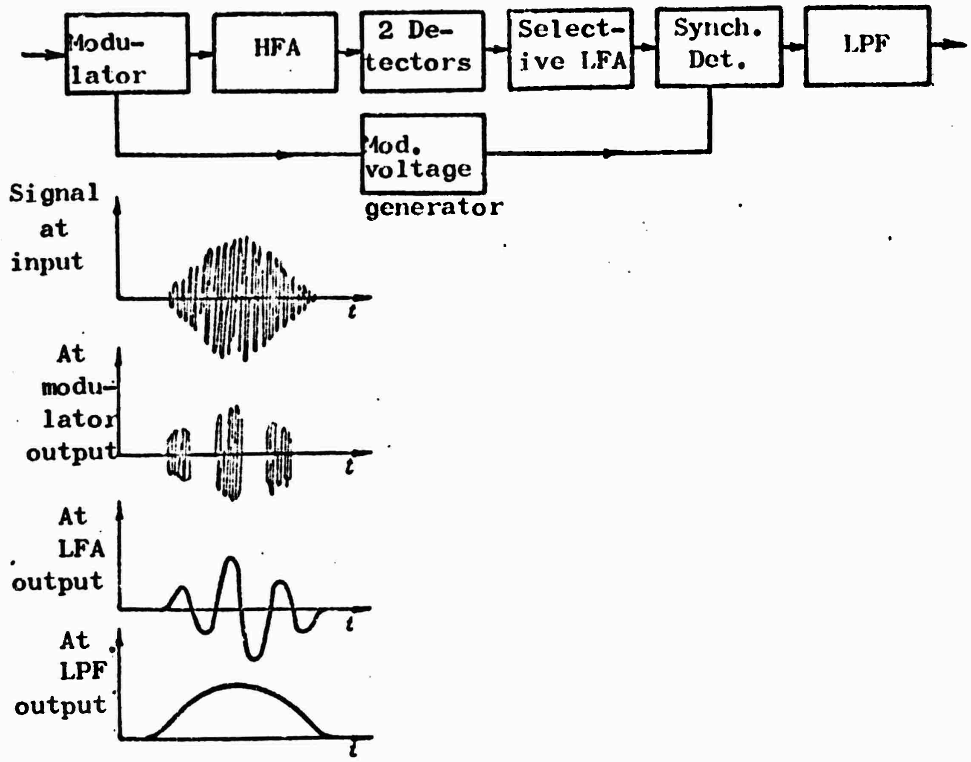


Figure 16. Functional diagram of modulated radiometer and voltage curves.

replacing the modulator with a switch that alternately connects the receiver input with the antenna output and with a noiseless ("cold") load. The load used in this case is a resistor cooled to a low temperature, or a small horn antenna pointed at a weakly radiating background.

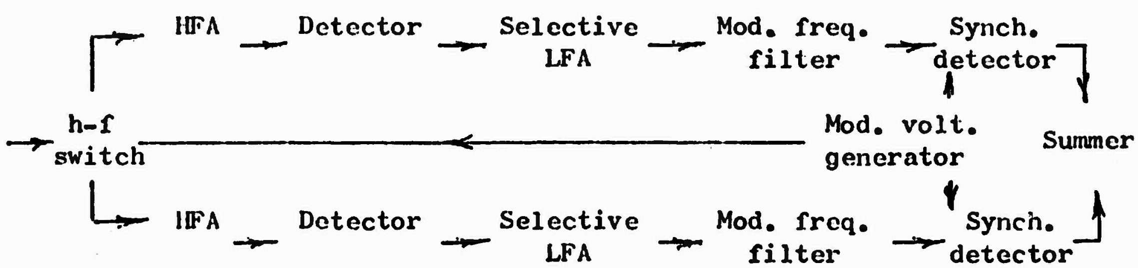


Figure 17. Functional schematic diagram of a two-cycle modulated radiometer.

Even more modern is the <u>two-cycle modulated radiometer</u> (Figure 17). As may be seen from the figure, the input switch continuously connects the antenna to the inputs of two receiving channels. The input signal /42 now can be converted into two sequences of rectangular h-f pulses, each

of which is amplified and detected in one of the reception channels. The summing of the detected and amplified pulses takes place in a two-cycle synchronous detector and a voltage that is proportional to the signal temperature is formed at the output.

The sensitivity of the two-cycle modulated radiometer is greater than that of the single-cycle because the input signal energy is fully utilized. But because the power of the internal noise too is increased (because of the noise from the additional reception channel) the sensitivity still is lower than that of the simplest radiometer, and is equal to

$$\Delta T_{tm} = \sqrt{2\Delta T}. \qquad (20)$$

An additional advantage of the two-cycle modulated radiometer is increased reliability. Operation still is possible in the conventional modulated radiometer mode in the event of failure of either of the channels. We should point out still another feature inherent in all the different types of modulated radiometers, and that is the need for a very careful match throughout the h-f tract. A poor match will result in the voltage generated by external receiver noise leaking to the antenna and being partially reflected by the antenna, only to once again appear at the receiver input via the modulator, or switch. Thus, some of the internal noise voltage will be modulated and separated at the output along with the useful signal. Clearly then, there will be a partial loss of the advantage gained by using the modulated reception principle. The requirement for a careful match leads to a more complicated, and more expensive, radiometer. This is why modulated radiometers sometimes are designed with a simplified circuit that modulates the detected signal (Figure 18). Fluctuations in the LFA gain are effectively eliminated in this radiometer, something that is very important because LFA radiometers, as distinguished from LFA receivers of all other types have very high gains with a magnitude that is very difficult to stabilize.

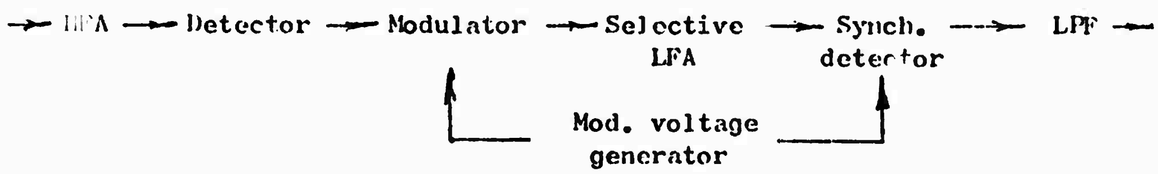


Figure 18. Radiometer with post-detector modulation.

Overall, the modulated radiometer can be characterized as a comparatively simple and reliable instrument that can be used to receive /43
thermal radio signals in all cases when there is no requirement for very accurate measurement of the temperature of incoming signals.

However, the modulated method is not the only one that can be used to cope with the harmful influence of gain fluctuations.

It is possible to use a variety of multichannel circuits, the most widely used of which is that of the correlation radiometer described above.

The correlation-modulated radiometer (Figure 19) is a unique hybrid of the correlation and modulated radiometers. A sum-difference bridge is connected across the input of the correlation-modulated radiometer, and the sum and difference of the input signals is picked off the two bridge outputs. Voltages proportional to the magnitudes $(u_1 + u_2)$ and $(u_1 - u_2)$ are supplied to the inputs of the detectors. After square-law detection, the maximum values of the rectified voltages are proportional respectively to $(u_1 + u_2)^2 = u_1^2 + u_2^2 + 2u_1u_2$, $(u_1 - u_2)^2 = u_1^2 + u_2^2 - 2u_1u_2$. Readily /44 seen is the fact that the difference in these voltages is equal to $(u_1 + u_2)^2 - (u_1 - u_2)^2 = 4u_1u_2$.

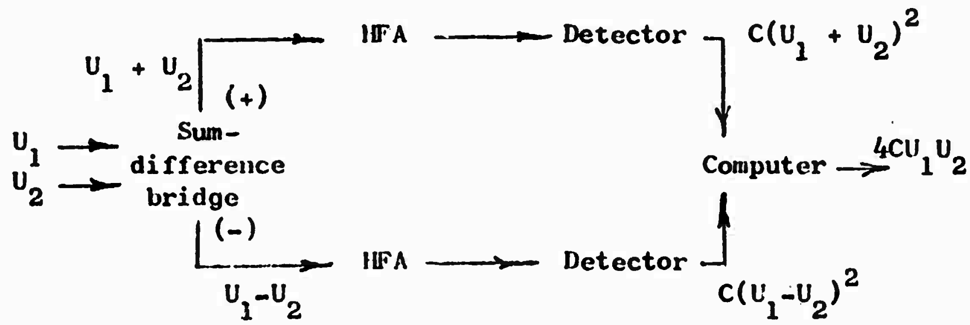


Figure 19. Functional diagram of a correlation-modulated radiometer.

<u>Accurate measurement of signal temperatures. Null radiometers.</u> There are times when measurements of the temperatures of thermal radio signals must be highly accurate. This would be the case, for example, when geophysical, and other, measurements are taken from thermal radio maps of a locality. In this case, just as in the case of other highly accurate radio engineering measurements, resort is had to the comparison method (Figure 20a).

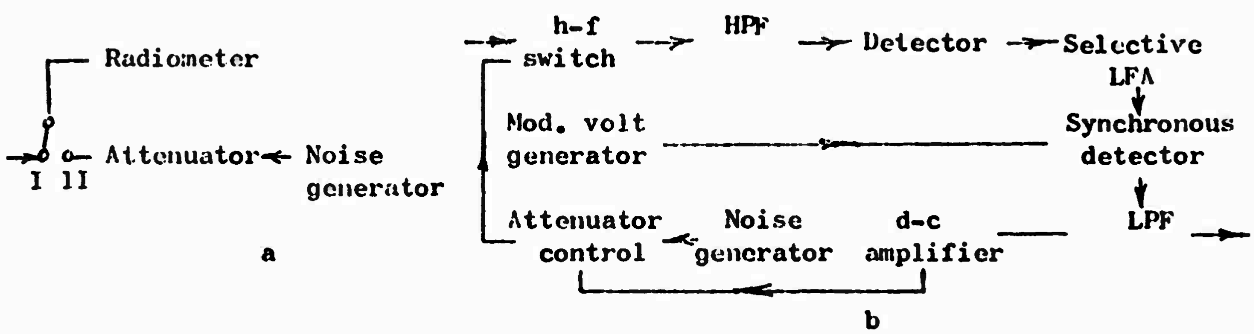


Figure 20. Functional diagrams of (a) a null radiometer and of (b) a null modulated radiometer.

Signal temperature is measured by periodically changing the position of the switch from I to II, and vice versa, and at the same time adjusting the position of the attenuator knob so that the meter reading remains the same during the switching. The use of a modulated radiometer is convenient in this arrangement because there is no need for manual switching and the

possibility of complete automation of the measurer is established (Figure 20b). As may be seen from the diagram, the radiometer's output voltage, proportional to the temperature difference, is amplified and supplied to the control attenuator. The simplest such attenuator consists of an electric motor and a conventional attenuator. The motor turns the shaft of the attenuator through reduction gearing, reducing the mismatch between the temperatures of the standard and measured signals. Accuracy of temperature measurement by the null method is in no way dependent on the stability of radiometer gain, and is governed solely by radiometer /45
sensitivity.

<u>Reliability in the reception of thermal radio signals.</u> Already pointed out is the fact that noise, primarily that generated in the input stages of receivers, interferes with reliable reception of thermal radio signals. Sometimes noise of external origin,* such as natural radio radiation from the terrestrial surface, the sun, cosmic sources, and the like, can be significant (we should point out that the limit to which it is desirable to reduce receiver internal noise depends on the level of external noise).

Quite obvious is the fact that reception reliability will be greater the higher the output s/n ratio. There is one basic difficulty in attempting to make a quantitative evaluation of reliability, however, and it involves the random nature of noise. It is possible to receive a noise "pulse" (a so-called "false alarm") as a signal when in fact there is no signal, even when the s/n ratios are high, or, on the other hand, there may be a signal, but it will not be noted because of the simultaneous reduction in the noise level. Noise will introduce an error in the measurement when measuring specific signal characteristics, and the magnitude of the error will change in a random fashion. It cannot be predicted, or calculated, accurately.

So what follows is that reception quality cannot be evaluated in absolutes, only in probabilities. Detection reliability usually is characterized by the probabilities of correct detection, P_d, and of false alarm, P_{fa}. Accuracy in the measurement of signal characteristics is evaluated by the probabilities of the appearance of errors of predetermined magnitude. Accordingly, the task of evaluating reception quality is one of determining the probable magnitudes in terms of a known output s/n ratio. The reverse of this must be solved when designing passive radars; find the magnitude of the s/n ratio needed to obtain these characteristics for a specified probability characteristic. The limited scope of this book does not permit dwelling in detail on the procedures /46
used to solve these problems, so we shall give and explain only the end results of the solutions.

Figure 21a shows the probability of correct detection and false alarm as a function of the magnitude of the s/n ratio at the output, calculated from foreign data [11]. Each curve is for a definite P_{fa}

* Only natural noise has been considered up to this point. The influence of organized noise will be discussed in the next chapter.

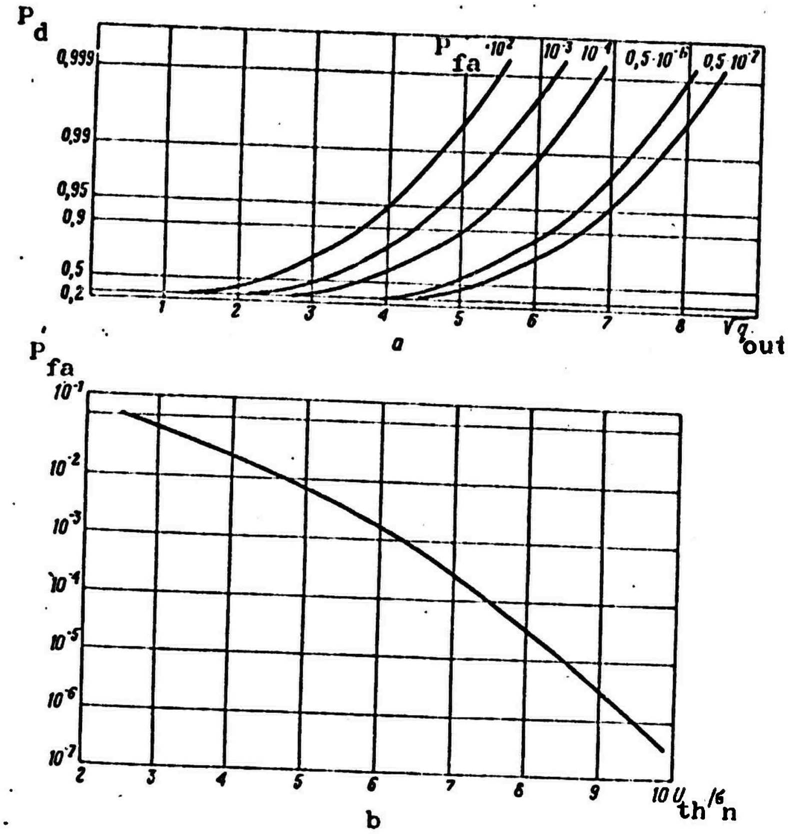


Figure 21. Probability relationships. (a) P_d and P_{fa} as a function of the s/n ratio; (b) P_{fa} as a function of the threshold level.

value for purposes of convenience. Accordingly, if the inverse problem is to be solved for a given P_{fa}, one selects the curve to find q_{out} that will satisfy the needed magnitude. The answer can be multivalued when determining the P_d and P_{fa} probabilities for a known q_{out}. There are several pairs of probability values for each q_{out} value. The true probability values in this case are determined from the accepted threshold level; by the value of the output voltage, the excess of which can be estimated as signal. The higher the threshold level selected, the lower the probability of a false alarm. The signal detection probability is somewhat reduced, however. /47

Figure 21a shows the false alarm probability as a function of the threshold level. The threshold level in Figure 21b is expressed in terms of the root-mean-square of the noise voltage at the output, and not in absolute units, so the curve shows the relationship between the magnitude of the noise pulses and the probability of their appearance. Note that the larger the pulses, the lower their probability. So we can reduce the danger of a false alarm to the needed level by increasing the threshold level. But now there is a requirement for a simultaneous increase in the s/n level in order to retain the high signal detection probability.

Let us now proceed to estimate reliability when measuring signal characteristics. The simplest, and at the same time the most widely used type of measurement in passive radar work, is that of the mean signal amplitude, or, what is virtually the same thing, the signal temperature. Already mentioned is the fact that when there is no signal the meter output voltage will fluctuate with a root-mean-square deflection proportional to ΔT, the sensitivity of the radiometer.

Accordingly, the root-mean-square of the error in the temperature measurement is simply equal to ΔT. Let us recall that the probability of the appearance of errors not exceeding the root-mean-square error is equal to 0.68. "Pulses" in errors exceeding $2\Delta T$ have a maximum probability of 0.05, while those exceeding $3\Delta T$ are possible with a probability of the order of 0.003. Note that these same results can be obtained from the curve which, as already has been pointed out, characterizes the probability of the appearance of "pulses" of random /48 noise. There is little probability of the appearance of errors exceeding $3\Delta T$ in absolute magnitude, so the results of temperature measurements can be considered reliable with accuracy of $\pm 3\Delta T$.

Errors in measurements of the time shift difference, and in the difference in Doppler frequencies, too are random magnitudes. Their root-mean-square values can be found from

$$\Delta t \simeq k_f/\Delta f \sqrt{q_{out}} \tag{21a}$$

$$\Delta F \simeq k_F/t_s \sqrt{q_{out}} \tag{21b}$$

where

k_f, k_F are coefficients of order unity;

t_s is the signal length.

The formulas at (21) are analogous to those used to calculate accuracy in measuring arrival time and Doppler shift in radar signals. The difference in the temporal shifts in thermal radio signals can be measured more accurately because the band, Δf, of thermal radio signals as a rule is greatly in excess of the frequency band for radar signals.

As may be seen from these formulas and curves, all that need be known in order to make a quantitative evaluation of reception reliability is one magnitude, the output s/n ratio, and this can be calculated by using Eqs. (16) and (17). There are many calculations when it is necessary to determine the input s/n ratio for the specified reliability. This value of the input s/n ratio is called the visibility factor in radar work. Readily proved by transforming the formula for the output s/n ratio is that the necessary visibility factor for reception of a thermal radio signal is equal to

$$q_m = T_{sm}/\Delta T = \sqrt{q_{out\ m}} \; . \tag{22}$$

Accordingly, the temperature of the input signal should be higher than the value of radiometer sensitivity, ΔT, by a factor of q_m, if reliability corresponding to the value of the output s/n ratio, $q_{out\ m}$, is to be ensured.

Characteristics of radiometer circuit. The main component of any radiometer is the receiver. Although radiometer receivers do have a great similarity to conventional radar receivers, there are in fact quite significant differences. The chief of these differences is the special requirements imposed on radiometer receivers; specifically the need to provide very wide h-f passbands, and an internal noise level as low as possible. Moreover, the gain and the noise figure for receivers should be very stable in order to prevent the appearance of additional l-f noise. /49

Just what are the basic principles underlying the design of r-f receivers? The first thing that must be pointed out here is the tendency to use amplifiers with low noise levels in input circuits. It should be pointed out that the development of passive radar is associated with the appearance of several types of low-noise amplifiers, something that provided the conditions for the development of much more sensitive receivers than the "classic" superheterodynes widely used in radars. It is known that the noise temperature of a multistage receiver can be found from

$$T_{n\,r} = T_{n\,f} + T_{n1}/\eta_f + T_{n2}/\eta_f k_{p1} + T_{n3}/\eta_f k_{p1} k_{p2} + \ldots, \quad (23)$$

where

$T_{n\,f}$, η_f are the noise temperature and efficiency of the input feeder, respectively;

$T_{n1(2,3)}$ is the noise temperature of the first (second, third) stages in the receiver;

$k_{p1(2,3)}$ is the power gain for the first (second, third) stages.

As may be seen from the formula, the use of an amplifier with a low noise temperature and a high gain in the first stage results in a sharp reduction in the receiver's noise temperature, even if the following stages have high noise temperatures. Moreover, the use of low-noise amplifiers will in many cases do away with the need to use superheterodyne reception, because adequate sensitivity can be obtained by using a two, or three-stage HFA. Practically all foreign radiometers in the centimeter band, and many radiometers in the millimeter band, have low-noise amplifiers in their HFA stages. The operating principles of these amplifiers, as well as their characteristics, have been described in detail in a number of books and texts published in recent years, so we shall limit our discussion of them to a brief comparison of their characteristics from the point of view of their usefulness in passive radar engineering. As we know, the main types of low-noise amplifiers developed to date are the: /50

special traveling wave tube (TWT);

parametric amplifiers (PA);

quantum-mechanical amplifier (QMA);

tunnel diode amplifier (TDA).

Let us review each of these amplifier types.

Historically, the first of the low-noise amplifiers was the TWT. These amplifiers, because of their quite wide passband, had quite high noise temperatures (5,000-15,000°K), so the possibility of using TWT to further increase the sensitivity of radiometers was found to be limited. The TWT uses an electron beam emitted by a heated cathode, so the main cause of noise is the well-known shot effect. It was long thought that there was a theoretically low limit to the TWT noise temperature at approximately 900°. Subsequently, however, it was shown that the noise could be reduced even further by improving the electrostatic and magnetic focusing of the electron beam.

It should be pointed out, however, that this improvement brings with it an increase in both weight and size (because, in particular, cumbersome and heavy magnetic systems are needed).

The foreign data on the subject show that modern, mass-produced TWT in the 3-cm band have a noise temperature in the 900-2,000°K range, and a passband equal to 20-30% of the carrier. Use of TWT such as these in the input stages of radiometers provides a sensitivity of a few hundredths of a degree.

Parametric amplifiers, particularly semiconductor diode parametric amplifiers (DPA), would appear to have quite a good future for use in radiometers.

As we know, there are a great many different types of diode parametric amplifiers, but foreign radiometric techniques will basically use single-circuit DPA that work on reflection. /51

Modern foreign DPA have noise temperatures between 80° and 300° in the 5-cm band, and between 300° and 500° in the 3-cm band when the gain is 10-18 dB. The passband is from 50 to 400 MHz.

Traveling wave DPA, which are delay lines with varactor diodes connected at several points, appear to have a good future. A signal supplied to the input of this type of amplifier will result in a rising signal wave in the delay line, and a pump wave moving along the line at the same time. The wide passband is the chief advantage of traveling wave DPA.

Parametric electronic amplifiers with a transverse field (Adler amplifiers) have been used successfully in the decimeter band, but have not yet been used in radiometry because a heavy increase in the intensity of the magnetizing field is required when the working frequency is increased.

Quantum-mechanical amplifiers (QMA) have the lowest noise temperatures. These amplifiers are used in radiometers for radioastronomy

purposes today. There are individual models of QMA with noise temperatures of no more than a few degrees. The drawback in resonator QMA, the limited width of the passband, has been eliminated in the intensively developed traveling wave QMA.

The traveling wave QMA is a decelerating system with built-in components of an amplifying material and the decoupling components needed to prevent self-excitation.

A ruby crystal is used in the 5-mm band traveling wave QMA developed in the United States. This amplifier has an internal noise of 2°K. The gain is 25-35 dB when the passband is 25 MHz.

Other countries are investigating the feasibility of designing QMA /52
to operate in the shortwave portion of the millimeter band, 4-6 mm in particular. It is proposed that the strong magnetic fields needed for QMA operation in the millimeter band be created by superconducting magnets. Thanks to unusually low noise temperatures, QMA can be expected to be used in fixed passive radar installations because the need for cooling to very low ("helium") temperatures, and the powerful magnetic fields required, will make it difficult to use QMA in airborne equipment. The DPA, although they have somewhat higher noise temperatures, do have very much better size and weight indices, and therefore will be much better suited for use in airborne passive radar.

Parametric, as well as quantum-mechanical, amplifiers have one drawback in common, and that is the requirement for a stable pumping source, the frequency of which should, as a minimum, exceed by a factor of two the working frequency of the amplifier. This first of all greatly reduces the feasibility of developing millimeter band amplifiers, and, second, leads to circuit complications because of the need to use networks of harmonic generators for pumping, more powerful and complicated supply sources, and the like.

This is why developers of radiometric techniques in foreign countries often must turn to tunnel diode amplifiers, the features of which include simple circuitry, economy, and extremely high reliability. A very important advantage of tunnel diode amplifiers is the high degree of resistance to external effects. Germanium diodes, for example, will operate stably from -200° to +100°C. The temperature range is even broader in silicon and gallium arsenide diodes. Extremely significant is the fact that tunnel diodes, as compared to other types of diodes, have better radiation resistance. Like the DPA and QMA, tunnel diode amplifiers can be designed for "pass through" and "reflection" schemes, as well as in the form of decelerating structures, including diodes ensuring a build-up of the signal wave traveling along the line.

The only sources of supply for the stages are the low-voltage /53
sources for bias voltage, with the magnitude of the power required from the source a maximum of a few milliwatts.

Foreign industry now is manufacturing tunnel diodes with a power gain of 12-15 dB and noise temperatures of the order of a few hundred degrees for use in the centimeter band and longwave part of the milli-

meter band. Cooling the diodes to low temperatures will further reduce noise temperatures. Cooling an amplifier to liquid nitrogen temperature (77°K) almost halves its noise temperature.

The tunnel diode is an electrical component with a negative resistance, so it can be used in the amplification, as well as in the oscillation, mode. It is true that the power of tunnel diode oscillators is low, but it can be increased a hundred-fold by using multidiode oscillators operating on the principle of a pump wave generated in the decelerating structure. Foreign experts are of the opinion that the use of tunnel diode circuits in the centimeter band (10-1.5 cm) is desirable.

Success achieved in the development of h-f, low-noise transistors now has made it possible to use transistorized HFA in radiometers operating on wavelengths longer than 10 cm. There still is no such thing as a simple, reliable HFA for radiometers operating in the shortwave region of the millimeter band, if one disregards the above-mentioned attempts to develop QMA. Deep cooling will substantially reduce the noise temperature of semiconductor HFA, input circuits, and frequency converters. High-frequency receiver units designed with cooling by liquid nitrogen, or helium, have been developed [8]. Nitrogen cooling is more economical than helium cooling, and requires nothing complicated in the way of equipment. Liquid oxygen equipment can be used for nitrogen cooling purposes, for example, at least according to the literature on the subject. Moreover, nitrogen cooling yields quite a good gain in noise /54 temperature. The noise temperature of nitrogen-cooled parametric amplifiers is a maximum of a few tens of degrees.

The passbands of cooled h-f units can vary from a few MHz to several hundred MHz, depending on the type of HFA used. The unit gain can be 15-30 dB. One Soviet-made cooled h-f unit has the following characteristics: $T_n = 50°$; $\Delta f = 32$ MHz; gain 16 dB.

Cooling also can reduce mixer and detector noise, something of particular importance for radiometers in the millimeter and submillimeter bands. We should point out that Soviet scientists and engineers were among the first to study the problem of cooling receiver units (see the bibliography at the end of the book).

If low-noise amplifiers are used in the input stages of a radiometer, succeeding parts of the radiometer circuitry can use direct amplification, provided by poorer quality amplifiers, or conventional superheterodyne circuitry. It is desirable for the receiver's i-f amplifier (IFA) to have a passband equal to that of the HFA in the latter case. The IFA must have special circuitry because the HFA has a width of tens of MHz, and more. The most widely used broadband IFA are those with distributed amplification and superhigh i-f amplifiers. And the development of transistorized conventional i-f amplifiers has been highly successful too. Modern foreign IFA have a passband of from 300 to 500 MHz, and a maximum noise figure of a few decibels.

Those foreign millimeter band radiometers without HFA usually have superheterodyne circuitry. The mixer stage and the first IFA stages are the chief noise sources in superheterodyne receivers, as we know.

Mixer noise can be greatly reduced by using mixer diodes made of tellurium with an admixture of gallium arsenide. The mixer diodes are rigidly secured in place inside waveguide flanges. This eliminates a series of parasitic effects, while sharply improving vibration stability in particular. The internal noise temperature in these mixers in the 3-4 mm band is a maximum of a few hundred degrees, and when low-noise IFA are used the overall receiver noise temperature is a maximum 7,000° in the 3.2 mm band, and 20,000°K in the 2.1 mm band. Radiometer sensitivities are 0.7-0.9°K and 2.4°K, respectively. It is of interest to note that the heterodynes in these receivers do not use vacuum tubes, but instead use a semiconductor element oscillator and a harmonic generator network that uses varactor diodes. There are those who believe superheterodyne receivers can be used for even higher frequencies, right up to 240 GHz (wavelength 1.25 mm). /55

There are a number of cases at frequencies higher than 100 GHz when it may be desirable to avoid using any of the radio engineering methods of reception, and go to optical type receivers similar to those used in the infrared band.

Low-temperature germanium bolometers, special photoresistors, those with an indium antimonide base, and certain other elements, can be used as such receivers. It should be emphasized that the operating principle of these receivers differs from that of radio engineering type receivers. Bolometers, photoresistors, and other, similar, elements directly convert the energy of the radio waves focused in them into d-c energy. These receivers, in other words, are unique radio wave detectors.

Optical type receivers have the following special features:

1. They have a wide passband. The passband as a rule is tens of percentage points of the working frequency.

2. There is no polarization selectivity. Optical receivers receive the whole signal, and this is where they differ from radio engineering reception systems that perceive the component of the radiation with just one type of polarization.

3. It is possible to increase signal power beyond the limits indicated by the "radio engineering" formulas. /56

The advantage of optical type receivers is the simple circuitry of the radiometers, which do not, in this case contain h-f components. Figure 22 shows the functional diagrams of radiometers with optical type receivers.

The radiometer in Figure 22a uses a so-called "field" modulator, a disk with alternating transparent and opaque sectors. The disk is mounted directly in front of the reception element and when rotated periodically interrupts the stream of thermal radio radiation focused on the surface of the receiving element. This causes an amplitude modulated signal to appear at the output of the reception element. The remainder of the circuit is similar to that of the conventional modulated radiometer. /57

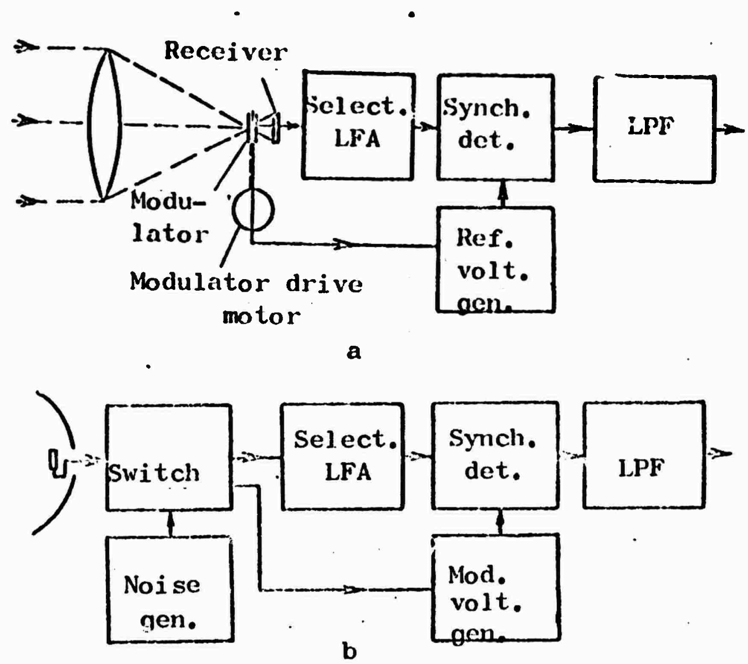


Figure 22. Functional diagram of a radiometer. (a) - with an "optical" receiver and a field modulator; (b) - with an "optical" receiver and a modulator.

The radiometer in Figure 22a uses a so-called "field" modulator, a disk with alternating transparent and opaque sectors. The disk is mounted directly in front of the reception element and when rotated periodically interrupts the stream of thermal radio radiation focused on the surface of the receiving element. This causes an amplitude modulated signal to appear at the output of the reception element. The remainder of the circuit is similar to that of the conventional modulated radiometer. /57

Figure 22b is that of a radiometer with an "optical" receiver and a signal comparison source. This circuit is somewhat similar to that of the null radiometer, and can be used for accurate measurements of signal amplitude. The shortcomings of the optical type receivers include, first, difficulty in using signal phase and frequency relationships, something that is necessary for radio interferometers and correlation radiometers, for example. Second, many optical type receivers, barretters and bolometers, for example, have an inertia factor of the order of units of milliseconds, something that interferes with their being used in passive radars with rapid space scan. Finally, it is very difficult to develop optical receivers with low noise temperatures.

Nevertheless, optical receivers have the best sensitivity at 1-2 mm wavelengths. A report published in the United States in 1965, discussed the development of radiometers with germanium bolometers for a wavelength of 1.2 mm. The sensitivity of these radiometers was 0.05°K, equal to the best of the centimeter band radiometers.

It is true that this sensitivity was obtained by cooling the reception elements to the temperature of liquid helium, but this does

not exclude the possibility of developing sensitive optical receivers that will operate at higher temperatures.

As we can see from the brief survey presented thus far, modern radiometric engineering has reached a high degree of perfection. But this does not mean that it is mandatory to use complicated special receivers with low-noise HFA, superwide IFA, supply voltage stabilizers, and the like, for passive radar purposes.

It is entirely possible to use the corresponding models of perfected radar receivers, including receivers in obsolete models, for many practical purposes; in particular for calibrating radar antennas for radio radiation from the Sun and Moon, and for the simplest thermal radio direction finders for Sun and Moon use. Let us, briefly, discuss the /58
basic concepts we should use for guidance when rebuilding receivers.

It is best to take the modulation radiometer as the basis for the circuitry because it is the least critical with resepct to receiver characteristics and supply voltage stability. In this case, modernizing the radar receiver means added to its circuitry an input modulator, an FM amplifier, a synchronous detector, a l-f output filter, and a reference voltage generator. Ferrite modulators, mass-produced by Soviet industry, can be used as the modulators. Diode modulators, as well as mechanical type modulators that are segments of a waveguide with a rotating disk partially embedded in the waveguide's longitudinal slot, can be used. Half of the disk is coated with an absorbing material so that the modulation is the result of absorption by this part of the disk. No changes need be made in the mixer. The gating circuit and the AGC are eliminated from the i-f amplifier. The gain of radar receivers usually is not high enough to realize temperature sensitivities of the order of a few degrees. The missing amplification can be obtained by adding a selective i-f amplifier to the receiver, the gain of which can be calculated as follows. First, determine the receiver's noise temperature from the formula

$$T_n \approx 7 \times 10^{(13-0.1m)}/\Delta f, \qquad (24)$$

where

m is the radar receiver sensitivity, dB/mW;

Δf is the receiver passband, MHz.

Then, proceeding from the desired radiometric sensitivity, determine the l-f output filter passband from the formula

$$\Delta F \approx 10^5 \Delta f \, (\Delta T/T_n)^2. \qquad (25)$$

Now use the value for ΔF to calculate the necessary LFA gain from the /59
formula

$$K_{LFA} \approx (1 - 2) \times 10^4 \sqrt{\Delta f/\Delta F}. \qquad (26)$$

EXAMPLE. A radar receiver has m = 100 dB/mW and Δf = 3.5 MHz. Then

$$T_n = 7 \times 10^{(13-0.1\times100)}/3.5 = 2000°$$

and to obtain the sensitivity $\Delta T = 1°$ we must have the following values

$$\Delta F = 10^5 \times 3.5\ (1/2000)^2 = 0.1\ \text{Hz};$$

$$K_{LFA} = 1.5 \times 10^4 \sqrt{3.5/0.1} = 90{,}000.$$

This sensitivity is quite high, so the l-f filter passband is narrow and the radiometer will be an inertia radiometer. If the sensitivity is limited to 4°, the passband can be taken as wider by a factor of 16, and the inertial nature of the filter will be about 0.6 second, rather than 10 seconds. And the needed LFA gain will be reduced to 20,000 at the same time.

The chief drawback of the majority of radar receivers, at least from the standpoint of radiometric use, is their comparatively narrow passbands. It therefore is more desirable to use direct TWT amplification receivers, the sensitivity of which can be much greater. The book by A. D. Kuz'min and A. Ye. Salomanovich, Radioastronomy Methods for Studying Antennas, provides more detailed information on the design of radiometric equipment.

3. Passive Radar Methods /60

Thermal Radio Signals as Information Carriers

The purpose of any location system is to obtain predetermined types of information about targets. The carriers of this information are signals, the parameters of which "code" target coordinates and characteristics. Information on range is coded in the time delay of the signals, target speed determines the Doppler shift in signal frequency, signal strength characterizes the size of the target in certain instances, and so on. Naturally enough, those location systems that provide a great deal of information about targets are the best.

The quantity of information a signal can carry depends significantly on signal properties. Theoretical and experimental research has established the fact that this quantity is proportional to the product of signal band times signal length, and signals from targets must be mutually independent if maximum information on several targets is to be obtained.

It is not difficult to see that thermal radio signals meet these requirements to a greater degree than do radar signals. Radar signals are greatly inferior to thermal radio signals where bandspread is concerned, and do not meet the requirement for mutual independence principally because they have a common source, a generator of radiation from an illuminated target. Thus, more information can be obtained about a target /61
from thermal radio signals than from radar signals. However, there is one important point that must be made, and that is that the incoming signals must be compared with reference signals if there is to be efficient extraction of information from those signals. This is the way target range and speed are established in radar work, for example. It is impossible to use reference signals in passive radar work, however, because the signal source is the target. Consequently, passive radar work must resort to using more complicated signal processing methods, ones based on a mutual comparison of signals received by spaced antennas, or put up with loss of part of the information.

The passive radars most widely used today are very simple single-channel sets that only measure the mean power of signals and the angular coordinates of the target. These passive radars cannot determine target range and speed, but can make extremely accurate measurements of intensity of radiation from targets, something that is not obtainable from radar. This was pointed out in the preceding chapter when the influence of Δf and t_s on the accuracy of measuring signal temperature was analyzed. So in this case the "information surplus" of the thermal radio signal is expended by increasing the accuracy with which signal power is measured. An even greater advantage of the thermal radio signal is apparent in two-channel passive radars, which can supply the range to targets, and their speed. It will be shown in what follows that broadband signals make it possible to improve the resolution of multichannel passive radars; that is, to increase the quantity of information obtained about targets.

What follows, therefore, is that the methods used to obtain information, and particularly methods used to obtain range and speed, from passive radar differ from radar methods. The only exceptions are the

methods used to obtain the angular coordinates which, as in radar methods, are based on the use of high-gain antennas. Methods used to extract information from thermal radio signals will be discussed in more detail in what follows. The discussion will begin with a description of the energy relationships (antenna temperatures as functions of apparent target temperatures), calculation of which is needed to evaluate the methods used to extract the information, as well as when calculating passive radar range. /62

Energy relations in passive radar. Let us begin the derivation of the energy relations with an explanation of one very important fact, our determination of the maximum value that the temperature of a thermal radio signal can reach. To this end we shall use Figure 23, which shows the most favorable case for the reception of a thermal radio signal, that of radiation from a very large (background) radiator received by a high-gain antenna. Let us assume the antenna to be ideal, that is, let us assume that there is but one main lobe in its pattern, and that within the limits of that lobe the directive gain (DG) is constant and equal to G, the antenna efficiency is unity, and there are no side lobes.

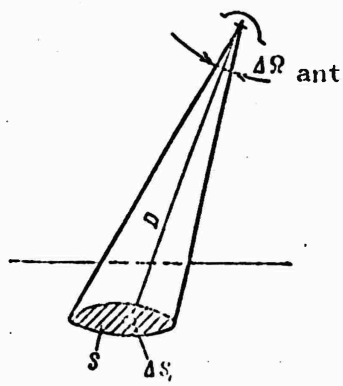


Figure 23. Illustration for the derivation of the antenna temperature formula for the case of a large area target.

As may be seen from the figure, the antenna perceives radiation from section S only because all the other sections of the radiating background are outside the limits of the antenna pattern. Then the radiation power flow from the smallest area, ΔS_1 incident at the receiving antenna will equal /63

$$\Delta I_1 = 2\pi k T_b \Delta S_1/\lambda^2 \times 1/2\pi D^2 = \Delta P_1 \times 1/2\pi D^2,$$

where

ΔP_1 is the power of thermal radio radiation in a 1 Hz band with area ΔS_1.

The power flow, ΔI_1, generates a signal at the antenna output, the power of which is

$$\Delta P_{a1} = \Delta I_1 A = kT_b G \Delta S_1 /4\pi D^2,$$

where

$A = G\lambda 2/4\pi$ is the effective area of the antenna in the receiving mode.

Signals from the entire area, ΔS, must be added in order to determine the power of the total signal from all of section S, thus

$$P_a = \Delta P_{a1} + \Delta P_{a2} + \ldots + \Delta P_{ai} + \ldots + \Delta P_n =$$

$$kT_b G/8\pi D^2 (\Delta S_1 + \Delta S_2 + \ldots + \Delta S_i + \ldots + \Delta S_n).$$

As may be seen from this latter formula, the power will be proportional to area S

$$P_a = kT_b GS/4\pi D^2 \qquad (27)$$

Let us point out, in order to obtain the final formula, that the magnitude S/D^2 is the solid angle covered by the pattern lobe. The magnitude of the solid angle is associated with the DG by a simple relationship

$$\Delta\Omega_{ant} = S/D^2 = 4\pi/G$$

(this latter expression indicating precisely what the DG signifies, that the main lobe is several times narrower than the whole solid angle, equal to 4π steradians).

Making the substitution, we find an unexpected result

$$P_a = kT_a = kT_b;$$

$$T_a = T_b, \qquad (28)$$

that is, the temperature of the thermal radio signal at the antenna output is equal to the apparent temperature of the radiation, and does not depend on the range, or on the directive properties of the antenna. /64

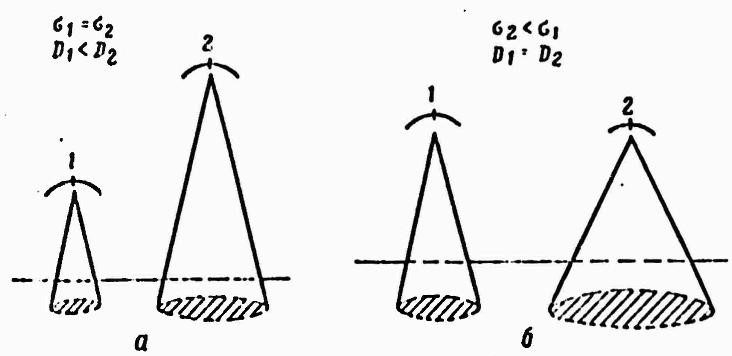


Figure 24. Reception of radiation from a large area target at different ranges and by antennas with different DG. a - different ranges case; b - different DG cases.

Consideration of Figure 24 will demonstrate the validity of this result. Actually, doubling the range to the target will increase area S by a factor of 4; that is, power and signal temperature being the same. As may be seen from Figure 24, there is no way to increase signal temperature, even by increasing the DG because if this is done area S will be decreased and P_a and T_a will remain unchanged. There is no method whereby T_a can be increased above T_b, nor will connecting several antennas in parallel help. Eq. (28) is based on a well-established physical principle directly associated with the second law of thermodynamics, and violation of this law would indicate that it is possible to "heat" the resistance of the antenna load from a "cold" source of radiation, that is, create a second order perpetual engine. Thus, Eq. (28) provides a magnitude for the limiting temperature of a thermal radio signal, that cannot be exceeded by any method.*

Eq. (28) will take the following form for real antennas /65

$$T_a = \eta\,(1 - \beta)\,T_{ap}, \qquad (29)$$

where

η is antenna efficiency;

β is the so-called scattering factor, characterizing the influence of the side lobes of the antenna pattern.

What follows from Eq. (29) is that the signal temperature is always lower than the apparent temperature of the radiator in the case of real antennas.

The use of Eqs. (27) and (28) make it easy to obtain expressions for antenna temperatures upon reception of radiation from small targets. If the target occupies a small (in terms of area) part of the pattern lobe, Eq. (27) can be used to write an expression for antenna temperature in the form

$$T_a = T_b G S_t / 4\pi D^2. \qquad (29a)$$

Using the equality $A = G\lambda^2/4\pi$, $\Delta\Omega_{ant} = \lambda^2/A$, we obtain

$$T_a = T_b\, A S_t/\lambda^2 D^2 = T_b\, \Delta\Omega_t/\Delta\Omega_{ant}, \qquad (30)$$

where

$\Delta\Omega_t = S_t/D^2$ is the solid angle for the target;

$\Delta\Omega_{ant}$ is the solid angle occupied by the antenna pattern.

---

* There are ways to increase the power of an incoming signal by using receivers of a non-radioengineering type. This will not, however, mean that Eq. (28) is violated.

There are correction factors that must be introduced in the efficiency and side lobes for real antennas, as in the preceding case.

$$T_a = \eta\,(1 - \beta)\,T_{ap}\,\Delta\Omega_t/\Delta\Omega_{ant}; \tag{31}$$

$$T_a = \eta\,(1 - \beta)\,T_{ap}GS_t/4\pi D^2. \tag{32}$$

The physical sense of the formulas is obvious. Decrease in target area means a reduction in the power of its radiation, and, consequently, a decrease in the antenna temperature. When the dimensions of the target are increased and reach those of the main lobe of the antenna pattern, Eqs. (30) and (31) are converted into Eqs. (28) and (29). Eq. (31) is convenient to use for practical calculations when the angular dimensions of the target are known. The solid angle, $\Delta\Omega_{ant}$, for real antennas can /66
be calculated using the formula

$$\Delta\Omega_{ant} = k_\Omega \Delta\varphi_{0.5}\Delta\theta_{0.5},$$

where

k_Ω is a conversion factor, equal to ~ 0.94, for antennas with a circular aperture, and ~ 1.3 for antennas with a rectangular aperture;

$\Delta\varphi_{0.5}$ ($\Delta\theta_{0.5}$) is the width of the antenna pattern in the azimuth elevation plane at the 0.5 power level.

Example. Calculate the antenna temperature for reception of radiation from the Sun in the 3 cm band with an antenna for which

$$\eta = 0.8;\ \beta = 0.3;\ \Delta\Omega_{0.5} = 5°.$$

The Sun's solid angle equals

$$\Delta\Omega_s \simeq \pi(\Delta\varphi_s)^2/4 = \pi 0.5^2/4 \simeq 0.225\ \mathrm{deg}^2,$$

where

$\Delta\Omega_s \simeq 0.5°$ is the Sun's angular dimension.

The solid angle of the main lobe of the antenna pattern is equal to

$$\Delta\Omega_a = 0.94 \cdot 5 \cdot 5 = 23.5°.$$

The apparent temperature of the Sun in the 3cm band is approximately equal to 20,000° K. Eq. (32) now will yield

$$T_a = 0.8\,(1 - 0.3)\,0.225/23.5 \cdot 2 \cdot 10^4 = 107°\mathrm{K}.$$

This is a very strong signal, at least from the point of view of radiometric reception. We should point out that the comparatively high antenna temperatures characteristic of reception of radio radiation

from the sun allows us to use this radiation to calibrate the antennas and receivers of conventional active radars.

As may be seen from the example given, Eq. (31) is handy to use to calculate the strength of a signal from very large objects at considerable distances.

It frequently is necessary, in practice, to estimate antenna temperature when receiving radiation from small objects, the area and range of which are known. Now it is more convenient to use Eq. (29a). It is better to use the conversion formula containing antenna area only if antenna* dimensions only are known, because this will avoid having to calculate DG /67

$$T_a = \eta (1 - \beta) AT_t\Omega_t/\lambda^2. \tag{33}$$

Note that in Eq. (33) the ratio of antenna temperature to the square of the wavelength is an inverse proportion. So if, in the example cited, we were to change the wavelength from 3 to 0.8 cm, antenna temperature would increase from 107° to 450° K, despite the fact that in the 8 mm band the apparent temperature of the sun is considerably lower than in the 3 cm band, and is only 6,000°K. We would obtain the same result if we were to use Eq. (31), because the width of the main lobe will be 1°50', and not 5°, when λ = 8 mm.

So, we have revealed yet another interesting property of thermal radio signals; the intensity of signals from elongated targets does not depend on the wavelength, and the intensity of signals from small-dimension targets is inversely proportional to the square of the wavelength. It can be shown quite readily that in the case of linear targets, that is, those with small width but long length, the antenna temperature as a function of wavelength will have an intermediate form

$$T_a \simeq \eta(1 - \beta)\, T_b\Delta\varphi_t d_{ant}/\lambda. \tag{34}$$

This can be explained by the fact that part of the main lobe of the antenna pattern containing a linear target will change linearly with change in the wavelength (see Figure 25).

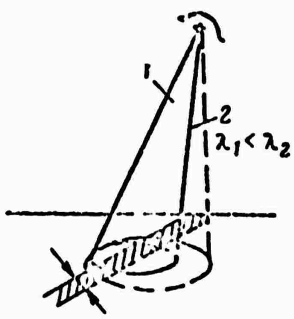


Figure 25. Reception of radiation from a linearly extended target.

*This is valid only when applicable to the area-type antennas, such as parabolic, lens, horn.

The difference in the frequency relationship of the antenna temperature is very important in practice because it can be used to select targets of the desired shape.

Signal length is highly important when separating information from incoming signals. We already have noted that the longer the signal the easier it is to detect, and the greater the accuracy in measuring signal parameters. Let us consider now the factors that determine signal length in passive radar work. Signal length can be found from the following /68
formula for passive surveillance radars

$$t_s = \Delta\varphi/\Omega_{sc}, \qquad (35)$$

where

Ω_{sc} is the scan angular velocity.

Signal length in this case can vary from microseconds to several minutes, depending on the width of the antenna pattern and on the scanning rate. Much longer signals are characteristic of passive tracking radars, but in order to obtain this length, that is, to use very narrowband LPF, it must be recognized that extraordinarily increased angular errors in tracking cannot be avoided. Consequently, the useful signal length for passive tracking radars seldom exceeds seconds, and it is only in special purpose passive radars (in radio sextants, for example) that signal length can be as long as several minutes.

The reception efficiency of signals is, to some extent, dependent on their shape. Signal shape is understood to mean the signal temperature, T_s, as a function of time

$$T_s(t) = M(t)T_{s\ max},$$

where

$T_{s\ max}$ is maximum signal temperature;

$M(t)$ is a function characterizing signal shape.

Signal shape will coincide with the shape of the antenna pattern (Figure 26a) in the case of passive surveillance radars working on small targets. In the case of an elongated target, one with a variable apparent temperature (so-called "thermal radio relief," Figure 26b), signal shape /69
will repeat change in the apparent temperature, but in a more even, smoother manner. The interesting analogy between the work of the antenna for a passive surveillance radar and the action of a l-f electrical filter must be pointed out. We know that a l-f filter will elongate short spikes and smooth out rapid fluctuations in the voltage supplied to its input. We will see this very same pattern in the scanning process if we replace the time axis with the axis of the sighting angles. As may be seen from Figure 26, a small target appears on the axis of the sighting angles as a

short pulse of apparent temperature with short "length," $\Delta\varphi_t$. We obtain a longer signal, one with "length $\Delta\varphi_{ant}$, during target scan. The smoothing out of spikes of apparent temperature when sighting elongated objects occurs similarly. This is why it sometimes is said that the antenna functions as a "space frequency filter." It is interesting that the conventional antenna "bandwidth" is proportional to the size of its aperture. The larger this dimension, the narrower the antenna pattern, /70 and, consequently, the shape of the signal pulse at the antenna output will approach the shape of the apparent temperature "pulse" perceived by the antenna during scanning.

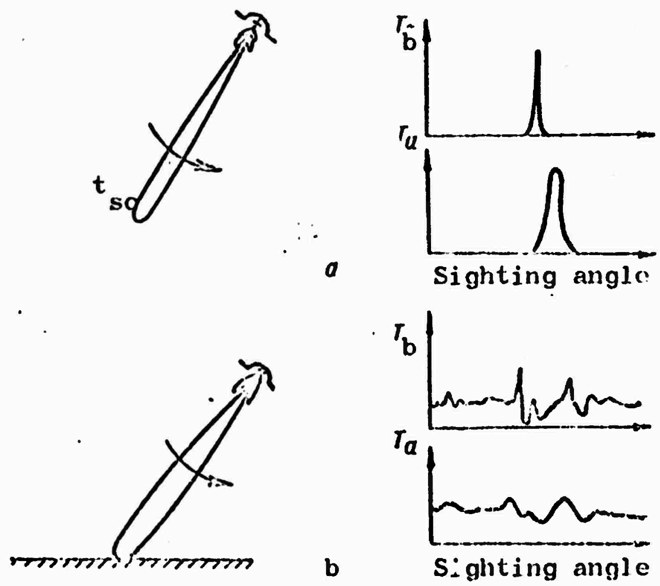


Figure 26. Distortion introduced by the antenna during scan.

Target detection when radiating backgrounds are present. Already pointed out has been the fact that the simplest passive radars cannot fix range to a target. Therefore, together with the useful signal from the target at the passive radar receiver input is other radiation, the sources of which are located along bearings close to the bearing to the target that has been detected. Thus, when air and ground objects are detected from an aircraft the interfering radiation will radiate from the terrestrial surface. In the case of ground-based passive radars working air targets, the interfering radiation will radiate from the atmosphere, clouds, and the sun. Radiation such as this, called background radiation, makes the detection of small targets exceedingly difficult for the following reasons. First of all, radiation from the background is added to the receiver's internal noise and, as a result, lessens receiver sensitivity. Second, radiation from the background masks radiation from the target, and in the limit case if the apparent temperature of the target and background are the same it generally is impossible to pick up the target. Third, inhomogenieties and spikes in the apparent temperature of the background can be mistaken for a target by a passive surveillance radar.

Recognizing the influence of the background, the formula for antenna temperature for a signal from a small target will take the form

$$T_a = T_{a\,t} - T_{a\,b} = \delta T_t \eta (1 - \beta) (\Delta\Omega_t/\Delta\Omega_{ant}), \tag{37}$$

where

$\delta T_t = T_t - T_b$ is the so-called radio brightness contrast between target and background.

Figure 27 will help explain the formula. Note that when the target is "hotter" than the background ($T_t > T_b$) the background detracts from target detection conditions. If the apparenttemperature of the background is higher than the apparent temperature of the target, detection can be improved because the radio brightness contrast between target and background can become greater than the apparent temperature of the target itself. The radio brightness temperature of a metal object, for example, that is not intensified by the background will be 120°-150°K; that is, the signal has been increased, so to speak, by a factor of many tens. Actually there has been no physical increase in the signal in this case, of course. The "shading" effect of the object has simply become well defined. /71

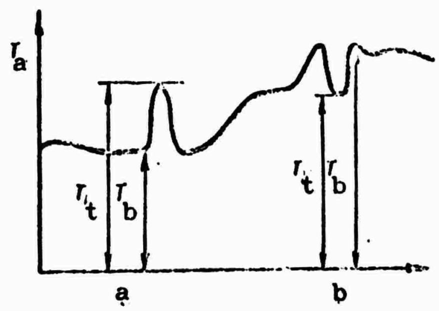


Figure 27. Radio brightness contrast between "target and background."
a - positive;
b - negative.

Nevertheless, it is desirable to get away from the influence of backgrounds when using passive surveillance radars. This can be done, for example, by using the difference in the polarization characteristics of background and target, as is being done most recently in active radar work.

Background radiation can be used as the signal radiation for passive radars used to measure track speed, and for thermal radio sensors of the vertical.

Operating principles and principal characteristics of passive surveillance radars. Passive surveillance radars are the ones most widely used at this time. Figure 28 is a functional diagram of a passive surveillance radar. As may be seen from the figure, this diagram contains the same elements found in the functional diagram for a surveillance radar, with the exception of a transmitter, an ATR switch, and a synchronizer.

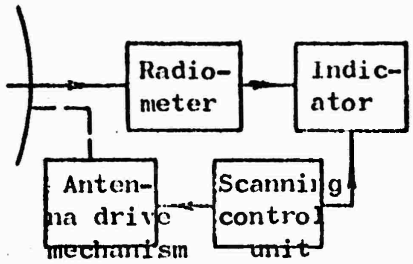


Figure 28. Functional diagram of a passive surveillance radar.

Antennas with a "needle" type pattern are the ones most often used with passive surveillance radars. This provides the means for fixing two angular coordinates of the target, but does complicate the antenna drive mechanisms somewhat. Passive radar can use different types of scan; line (raster), spiral, cycloidal. So-called single-line scan, used in airborne passive surveillance radars (Figure 29), is special. In single-line scan the needle antenna beam scans in a plane perpendicular to the

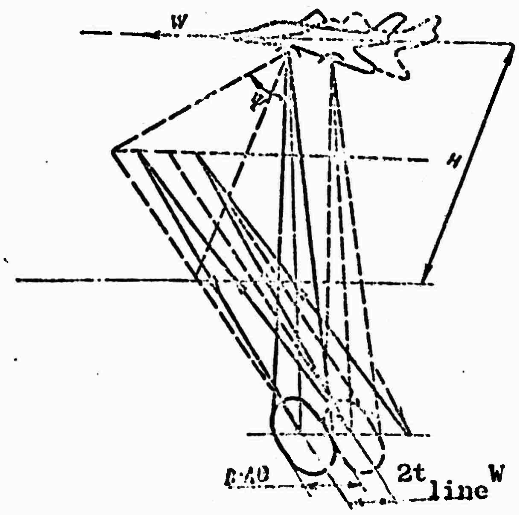


Figure 29. Single-line scan.

axis of the aircraft, providing scan on both sides of the flight trajectory. The line of flight is scanned by maneuvering the aircraft. /73

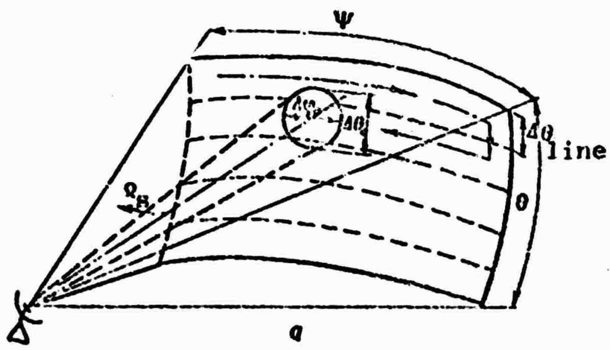


Figure 30. Raster scan.

The principal characteristics of a surveillance radar are range and resolution. Let us see how these characteristics are linked to the parameters of the passive radar and the target. First of all, let us determine the signal length corresponding to one element of the scan. If the dimensions of the scan zone are given by angles θ (elevation) and Ψ azimuth, and if the angular width of the antenna pattern is made up of $\Delta\varphi$ and $\Delta\theta$, (Figure 30), each element in the zone with dimensions equal to those of the antenna pattern will be looked at for time

$$t_s = k_t \Delta\varphi\Delta\theta T_{sc}/\psi\theta \quad (38)$$

where

k_t is the line overlap reserve factor;

T_{sc} is the specified zone scan time.

The sense of Eq. (38) is quite obvious. The smaller the solid angle of the antenna pattern as compared to the solid angle of the scan zone, the longer the time that will be devoted to looking at a single element in the zone, as compared to the time spent on scanning the entire assigned zone. It is more convenient to express subsequent calculations of $\Delta\varphi$ and $\Delta\theta$ in Eq. (38) in terms of the magnitude of the DG, as we did in the antenna temperature calculations /74

$$t_s = k_t k_1 4\pi T_{sc}/G\psi\theta \quad (39)$$

The time required to look at an element in the zone, t_s, is equal to the signal length obtained from a small target, so, if a radiometer with noise temperature T_n and a h-f passband of Δf is used in a passive surveillance radar, its sensitivity will be equal to

$$\Delta T = T_n/\sqrt{\Delta f t_s} = T_n\sqrt{G\psi\theta/4\pi k_t k_1 \Delta f T_{sc}} \quad (40)$$

The signal from a target must exceed the magnitude of the sensitivity, ΔT, by a factor of "q_m" if reliable detection of the target is to be obtained

$$T_{a\,t} \geqslant q_m \Delta T. \quad (41)$$

The magnitude q_m is selected from the condition of a specified detection probability. Substituting the expression for target antenna temperature from Eq. (29a) into the left-hand side of the relationship at (41), and with Eq.(40) taken into consideration, we obtain

$$\delta T_t S_t G/4\pi D^2 \geqslant q T_n\sqrt{G\psi\theta/4\pi k_t k_1 \Delta f T_{sc}}.$$

Solving for D, we obtain the formula for the range of a passive surveillance radar as

$$D = \sqrt{\Delta T_t S_t/4\pi q T_n \quad \sqrt{4\pi k_1 k_t \Delta f G/\psi\theta}} \, . \qquad (42)$$

Let us analyze this formula. The range is proportional to the square root of the product of the radio brightness contrast for the target and its area, and inversely proportional to the root of the radiometer sensitivity. The dependence of the range on the antenna DG, and on the dimensions of the zone scanned, is much weaker (proportional to the fourth root). The explanation of this difference is simple. Time t_s decreases with increase in antenna DG. Thus, a rise in the target antenna temperature is partially balanced by a reduction in signal length. A form that is more convenient for practical use, arrived at by uncomplicated transformations, and by substitution of numerical values for the coefficients in Eq. (42), is /75

$$D \simeq 0.135 \sqrt{\delta T_t S_t/\Delta T q_m} \cdot \sqrt[4]{T_{sc}/\psi\theta\Delta\varphi\Delta\theta}, \text{ km.} \qquad (43)$$

The magnitudes in (43) have the following dimensionalities: S_t is in m^2, δT_t and ΔT are in °K; T_{sc} is in seconds, and Ψ, θ, $\Delta\varphi$, $\Delta\theta$ are in degrees of angle. The antenna beam angles in this case are taken at the zero level.

Calculations made using the relationship at (43) show that the range of passive surveillance radars can be quite great. A passive radar with $\Delta T = 0.01°$; $\Psi = \theta = 10°$; $\Delta\varphi = \Delta\theta = 1°$; and $T_{sc} = 1$ sec, for example, is capable of reliable ($q_m = 5$) detection of an object with $\delta T_t S_t = 5000° \cdot m^2$ at ranges in excess of 10 km.

Practically speaking, there are many cases when the range is limited by inhomogeneities in the apparent temperature of the background, and not by radiometer sensitivity. These generate additional noise during scanning that is similar to fluctuations in the radiometric gain factor discussed in Chapter 2. In these cases some improvement can be achieved by using special l-f filters that separate out the short signals from small targets from the longer spikes caused by the inhomogeneities in the background radiation.

A second method used to compensate for the harmful influence of background inhomogeneities is based on the use of a recording of the radiometer output voltage over a period comprising several scan cycles. This is followed by paired subtraction of recordings of adjacent scan cycles, using a special device. The result of the subtraction is to balance out the background and retain the recording of the useful signal (see Figure 31).

Passive surveillance radar of the type described is designed to scan an air space. Airborne passive radars for scanning the terrestrial surface are somewhat different. They use a single-line scan mode (Figure 29) and range will be expressed by another formula. Let us derive this formula. The scanning rate in the transverse plane should be selected such that there is some overlap of adjacent lines. Given this condition, the scan time for one line will equal /76

$$t_{line} = k_1 D \sin \Delta\theta/2W \approx k_1 D\Delta\theta/2W,$$

where

D is the distance to the extreme points in the zone scanned;

W is flight speed;

k_1 is the line overlap factor.

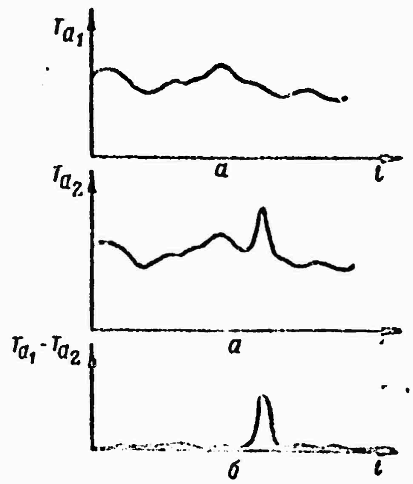


Figure 31. Balancing the influence of the background. a - signal recordings before subtraction; b - the result of subtraction.

Knowing the time to survey one line, it is not difficult to find the time to survey one element (signal length)

$$t_s - t_{line} \quad \Delta\theta/\theta. \tag{44}$$

Using the relationships in (38-42), the distance formula can be obtained as

$$D \simeq 0.12 \quad \sqrt[3]{(\delta T_t S_t/\Delta T q_m)^2 \quad 1/W\psi\Delta\varphi\Delta\theta}. \tag{45}$$

This formula differs significantly from Eq. (42).

First of all, there is the dependence on flight speed, and second, there is the strong influence of the antenna pattern width, contrast, and target area. This explains the more complex dependence of signal length on $\Delta\varphi$, $\Delta\theta$ and ψ. /77

Resolution, that is the minimum distance between two targets in an area at which the two still can be seen as separate targets, is an important parameter of a passive radar used to scan the terrestrial surface. Resolution depends on antenna pattern width and range to the targets in the following way

$$\Delta L_{az} = D \sin \Delta\varphi \simeq D\Delta\varphi; \quad (46a)$$

$$\Delta L_{ts} = D \sin \Delta\theta / \cos \psi/2 \simeq D\, \Delta\theta/\cos \psi/2 \quad (46b)$$

The azimuth resolution will deteriorate more rapidly with increase in the range, so that the detail of the image of the terrestrial surface obtained along the edges of the scanned zone will be of poorer quality than those in the middle.

The best resolution is equal to

$$\Delta L_{az} = H \sin \Delta\varphi \simeq H\Delta\varphi \quad (47a)$$

$$\Delta L_{ts} = H \sin \Delta\theta/\cos \psi/2 \simeq H\, \Delta\theta/\cos \psi/2. \quad (47b)$$

will be at zero azimuth angle. This means that the terrain sections directly beneath the aircraft carrying the passive radar will be reproduced in the sharpest detail. This is an important advantage of the passive surveillance radar over airborne panoramic radars which, as is known, have very low resolution at short ranges. We also should point out that the resolution of foreign passive radars is in meters and less at short ranges and when antenna patterns are sufficiently narrow, and this, practically speaking, is unattainable with conventional radars.

Multichannel passive surveillance radars. The problem of radio vision. We already have seen that expansion of the scanned zone will reduce the range of passive radars. Furthermore, scanning time will be increased if the scanned zone is expanded, and this often is undesirable. /78

This drawback is overcome by designing passive radars with multiple channels so that the whole of the zone to be scanned is divided into several smaller zones. The range of a passive radar with multiline scan will be increased by a factor of $\sqrt[4]{n}$ if there are n channels functioning simultaneously, rather than just one channel. The range of an airborne passive surveillance radar will be increased by a factor of $\sqrt[3]{n}$. There is absolutely no need to make each channel in the form of an independent passive radar. Modern antenna engineering can design antennas with several spaced patterns, and it is antennas such as these that are used with multichannel passive radars. There can be a common scope as well. This means that only a few radiometers are needed. An important advantage of multichannel passive radar is better reliability because it can continue to function on the good channels should one channel of a multichannel passive radar fail.

If the number of channels is taken as very large, a space can be covered without scanning (Figure 32). This coverage method is called radio vision. "Radio vision" is not an arbitrary term. The fact is that thermal radio radiation, like light, is incoherent and broadband. This is why thermal radio images of terrain sections strongly resemble the images of these same sections as seen by the eye (Figure 33). Radio vision is a complex technical problem, primarily because the number of

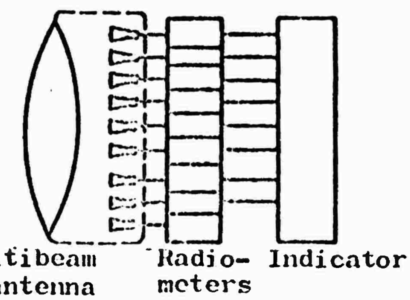


Figure 32. The principle of radio vision.

receiving channels is so great, hundreds, or even thousands. This is why superminiaturized models, and sufficiently cheap radiometers, have not yet been developed. It still is too soon to talk about the widespread use of radio vision. /79

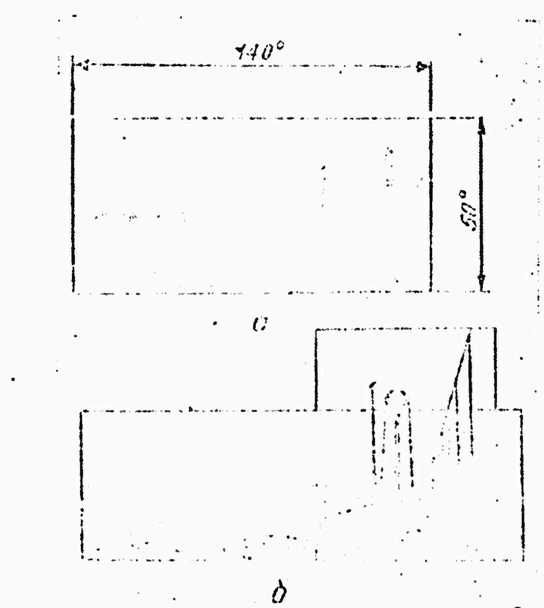


Figure 33. A thermal radio image of a terrain (a) and a photograph of the same terrain section (b).

Passive tracking radars. Passive tracking radars are designed to automatically track single thermal radio targets by angular coordinates. The operating principle and functional schematic of the passive tracking radar are quite similar to those of conventional tracking radars. Conical scan is most often used in passive tracking radars. Figure 34 is a functional diagram of a passive radar of this type.

Just as in the case of the tracking radar, the input signal is amplitude modulated because of rotation of the antenna pattern, and the /80

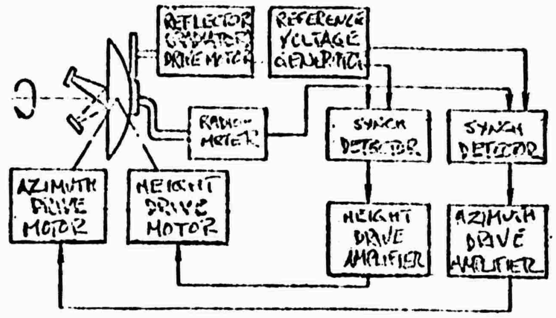


Figure 34. Functional diagram of a passive tracking radar with conical scan.

depth of modulation increases with distance of the source of radiation from the axis of rotation. The phase of the modulation is determined by the direction in which the source is shifted. There is no need to use a modulation radiometer in a passive tracking radar because the incoming signal already is modulated. The signal therefore is supplied to a narrow band l-f amplifier tuned to the modulation frequency after detection. Synchronous detectors are connected to the amplifier output and direct current voltages are formed at their outputs. These voltages are proportional to the magnitude of the angular mismatch between the axis of rotation of the antenna pattern and the direction to the source on which the bearing is being taken. These voltages also are used to control the antenna drive mechanisms, thus providing for automatic tracking of the source of thermal radio radiation. The principal characteristics of the passive tracking radar are operating range and accuracy in fixing angular coordinates.

Eqs. (38)-(42) can be used to find the operating range. Simple mathematical transformations of these latter will yield

$$D \simeq 0.1 \sqrt{\delta T_t S_t / \Delta T q_m \Delta\varphi\Delta\theta} \cdot \sqrt[4]{t_s}. \qquad (48)$$

Derivation of the formula for the error in angular tracking is quite complicated, so we shall simply provide the result as /81

$$\sigma_\varphi \simeq 0.4 \, (\Delta\Psi_{0.5}/q_m \sqrt{t_s}) \quad , \qquad (49)$$

where

$\sigma\varphi$ is the root-mean-square of the error in angular tracking resulting from internal noises in the passive radar's radiometer.

The harmful influence of internal noise appears in this case, because some of the detected internal noise enters the passband of the narrow band i-f amplifier, passes through the synchronous detectors and power amplifiers, and causes the passive radar antenna to oscillate in a random fashion.

As may be seen from the formula at (49), the magnitude of these oscillations can decrease, narrowing the passband of the low-pass output filter. This narrowing of the band reflects favorably on the operating range of the passive radar as well [see formula (48)]. It would appear

that the use of very narrow-band filters would result in highly accurate angular tracking and long operating range. However, there is a dynamic error in angular tracking that increases with increase in instrument inertia, and this is in addition to the random error in angular tracking, $\sigma\varphi$. So it follows that the passband of the low-pass filter must be selected such that the summed error will be least.

A drawback in the passive tracking radar with conical scan is the dependence of the accuracy of the angular tracking on the width of the antenna pattern. If, for whatever reason, a sufficiently large antenna cannot be used with the passive radar, other ways to increase accuracy must be sought. One possibility is the use of phase direction finding methods. Figure 35 is a functional diagram of a tracking phase direction finder. The phase direction finder uses two antennas spaced distance <u>a</u> apart on a base line. The signals from the antennas are fed into the two inputs of a correlation radiometer. A controlled phase-shifter is inserted in one of the input circuits. Let us suppose that the shifter initially is set for zero phase shift. Then, if the signal source is equidistant from both antennas, that is, if the source is on a bearing perpendicular to the base at its midpoint, the phases of both input signals will be /82
equal and the output voltage from the radiometer will be a maximum. If, however, the bearing to the sources does not coincide with this perpendicular there will be a relative phase shift that will result in a reduction in the output voltage. The output signal will be zero when the phase shift is 90°. The signal will become negative with further increase in the shift, becoming equal to the signal corresponding to the "equal phase" bearing when the phase shift is 180°, and, as before, will have a negative sign. As may be seen from the figure, the phase shift equals

$$\Delta\psi = 360° \,(a/\lambda)\sin\varphi.$$

As may be seen from this formula, the longer the base, "a", the greater will be the phase shift in the input signals for the same angular deflection of source φ; that is, the greater will be the direction finding sensitivity of the system.

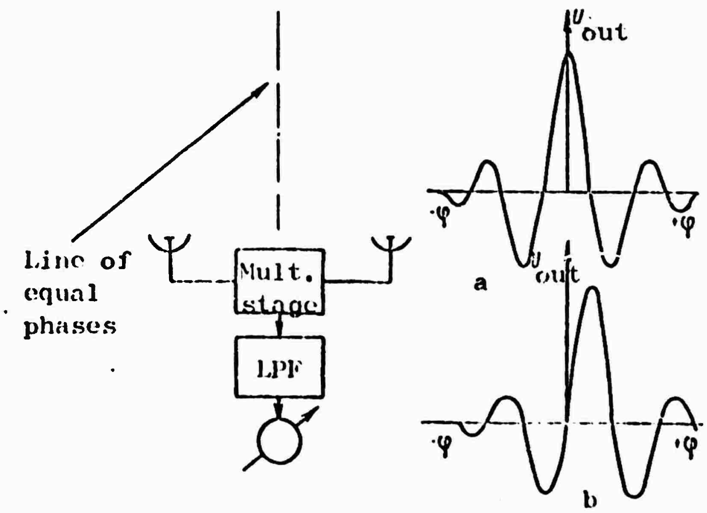


Figure 35. Functional diagram of a phase radio direction finder.

Accordingly, the direction finding sensitivity of a passive phase radar is determined by the length of the base line, and is virtually independent of antenna size. A phase-shifter that shifts signal phase 90° is inserted in one of the input arms of the phase direction finder to separate the signal from the error. The voltage across the output of the radiometer will be zero when the bearing to the source coincides with the equal phase line, and error signals with different signs will appear when there is a deflection to the left or right. These signals are supplied to a d-c amplifier. An electric motor is connected to the output of the amplifier. The shaft of the electric motor is coupled to the shaft of the phase-shifter through reduction gearing. This system provides automatic tracking of the signal source, and the bearing can be read directly from the angle of rotation of the phase-shifter. /83

There are other variants of arrangements for tracking phase thermal radio direction finders. As has been noted, the direction finding sensitivity of the phase direction finder can be made very high by increasing the base line. There is a limitation however. If the base line is very much longer than the wavelength, the direction finding characteristics will become multivalued, and false nulls and maxima will appear. Ambiguity in readings is a drawback, so the use of long base lines is undesirable f r radio direction finders. The effect can, however, be used in special passive radars known as radiointerferometric radars, and they will be discussed in what follows.

Selection of thermal radio signals. Range and speed measurement. The capability to make separate observations of targets that may be at different ranges, and to measure those ranges, is the most valuable property of radar, but is unusually difficult to realize with the passive radar. The simplest single-channel passive radar cannot measure the range to a detected target, or determine how one, or several targets within the beam of the antenna pattern may be distributed with respect to range. This passive radar will reproduce the thermal radio radiation from a target a few kilometers distant, and the radio radiation from the sun, 150,000,000 km away, in exactly the same way. And since the earth, or the sky, always is within the field of view of a passive radar, it is clear that absence of range selection is primarily the result of ever-present noise from distant background sources. The useful signal has to be separated from all this noise. /84

Equipment for selecting signals from targets out of a background of interfering radiation is required for the efficient operation of passive radars. There are, today, several known types of selection that can be used to solve this problem. These types of selection are based on the following differences between targets and noise sources (backgrounds):

difference in radiation spectra;

difference in polarization characteristics;

difference in dimensions;

difference in speed of movement.

None of the above excludes the development of special types of range selection for passive radars.

Let us take up these types of selection in somewhat more detail. The simplest type of selection is spectral selection, wherein the difference in the spectra of radiation from the target and the noise source is used. Unfortunately, this selection method cannot be used to distinguish small targets against "hot" backgrounds, against the background of the terrestrial surface, for example. On the other hand, spectral selection is very useful for detecting airborne targets against a background of clouds and a radiating atmosphere. Correct selection of the passive radar band can sharply reduce the influence radiation from the atmosphere and clouds will have on passive radar performance.

Polarization selection obviously can give reasonably good results. The gist of polarized selection is that both components of thermal radio radiation are received simultaneously by two separate radiometers. If the polarization characteristics of targets and backgrounds are known, a comparison of signals received by two channels will separate the target signals.

There are several different functional arrangements that can be used to make the selection in terms of signal source dimensions. Multifrequency reception is one approach. We already have pointed out the fact that antenna temperature increases with increase in the working frequency of the receiver when receiving signals from small targets, as well as the fact that antenna temperature does not depend on the frequency in the case of extended targets (backgrounds). So we can make a decision as to the presence, or absence, of a small target by comparing the output signals from two radiometers tuned to different frequencies, even if radiation from the background is received simultaneously. It is possible to differentiate to some degree between target sizes, even using conventional single-frequency reception, if the passive radar antenna has a very narrow pattern. It is quite obvious that signals from more extended targets picked up during scanning will have greater length than will signals from small targets. However, this difference will not be clear cut unless the extent of the target is such that its angular dimensions are greater than the dimensions of the antenna pattern. It is practically impossible to use this method to distinguish targets by their size when they occupy a small part of the main lobe. And space limitations often make it impossible to use antennas with narrow patterns. In these cases we can use radio interferometers, passive phase radars with long base lines, for selecting targets by size. Figure 36 shows the operating principle on which the radio interferometer is based. The base line for the radio interferometer is chosen comparatively long, of the order of hundreds, or even thousands, of wavelengths. We already have seen that in this case the direction finding characteristic will become multivalued. This means the resultant antenna pattern will have a great many lobes. The number of lobes will depend on the ratio of the length of the base line to the wavelength and antenna pattern width /85

$$n_1 \simeq \Delta\varphi(a/\lambda) \simeq 70(a/d_{ant}) .$$

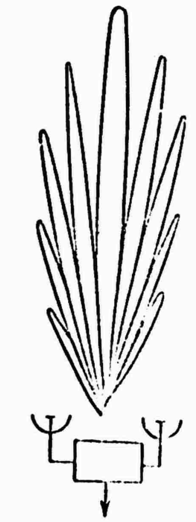


Figure 36. Radio interferometer antenna pattern.

A multilobed pattern such as this scanning a point target will yield a voltage at the radio interferometer output with a changing sign reminiscent of a radio pulse because the target will pass through opposite sign lobes in the pattern. /86

The length of the output "radio pulse" will, like that for a conventional passive surveillance radar, equal

$$\tau \simeq \Delta\varphi/\Omega_{sc},$$

and the fill frequency will depend on the number of lobes and on the scanning rate .

$$F_f \simeq a/\lambda\ \Omega_{sc} \qquad (50)$$

Let us now see what happens if a target with an angular dimension less than the aperture of the antenna pattern, but larger than the angular dimension of one lobe, enters the radio interferometer's field of view. The figure makes it clear that a target such as this will overlap lobes with different signs and its signal will be weaker than that from a point target. The signal from this target will be zero if the target dimension is equal to twice the dimension of the lobe, because each half of the target will generate a signal of opposite sign, and the two will cancel each other. The picture is similar when the target dimensions exceed the width of the pattern's main lobe. So we see that the radio interferometer is a fine instrument for selecting targets in terms of their dimensions. One example of this fact is the use by astronomers of radio interferometers to obtain a detailed picture of the distribution of the solar surface radio brightness temperature. The width of the patterns of the antennas used for the purpose is greatly in excess of the sun's angular dimensions. So it follows that the radio interferometer provides a reproduction of radio brightness relief with incomparably more detail than is possible by using single-channel passive radars, and this is in addition to target selection in terms of dimensions. In

other words, the radio interferometer substantially increases angular resolution without the need to increase antenna dimensions. We shall take up this property of the radio interferometer in somewhat more detail later on.

Now let us consider speed selection capabilities. The conventional radar performs the speed selection chore by simple separation of the Doppler shift in the frequencies of incoming signals. This chore is much more complicated in the case of passive radar, however, because, first, there are no reference signals, and, second, because of the broadband nature of thermal radio radiation. Passive radar therefore goes about the speed selection task by using a variety of indirect methods. The simplest form of speed selection is suppression of signals from fixed targets. One such method for suppressing signals from fixed targets, and which is, to some degree, analogous to alternate period subtraction, was described above (see Figure 31). Moreover, the ratio of target signal length to target speed can be used for target selection based on speed. Signal length is a function of target dimensions, and scanning rate, in the case of fixed targets. But if a target is moving in a plane perpendicular to the axis of the antenna pattern, the length of the signal from that target will be decreased, or increased, depending on whether the direction of motion coincides with the direction of scan, or is opposite to it. The radio interferometer described above can be used effectively for speed selection. Let us take up in more detail the principle involved when a radio interferometer is operating in the target speed selection mode. We already have seen [formula (59)] that the fill frequency of the interferometer's output signal is directly proportional to the scanning rate. Now let us be persuaded that the interferometer's pattern is not scanning, and that a target moves through the pattern at speed W at distance D (Figure 37). This target movement is equivalent to scanning at an angular velocity of $\Omega = W/D$. Substituting this expression into formula (50), we obtain for signal frequency /87

$$F_f \simeq a/\lambda \; W/D.$$

All the magnitudes in this formula, except W and D, are known, and frequency F_f can be filtered out and accurately measured, so the following conclusions can be drawn:

(1) The radio interferometer can select targets in terms of speed, as well as in terms of range (because targets flying at the same speed, but at different ranges, will yield output signals with different frequencies, F_f); /88

(2) the radio interferometer can be used to measure speed and range to target, but the results of the measurement will not be single-valued because targets with different D and W can equate to the same frequency, assuming their ratios to be equal. More precisely, the radio interferometer selects a target in terms of its angular, not linear, velocity, equal to the W/D ratio. Herein is the chief drawback in the radio interferometer selection method; the inability to separate targets with very low angular velocities (distant and slow speed targets, for example),

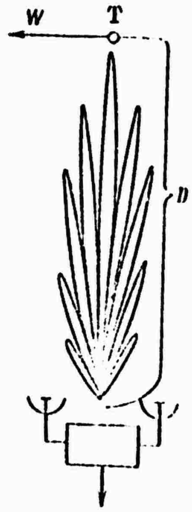


Figure 37. Principle involved in the use of a radio interferometer to measure speed and distance.

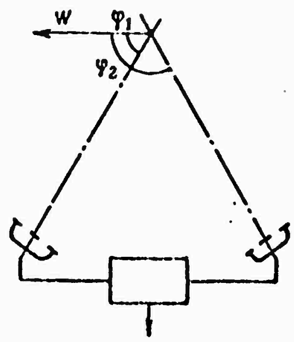


Figure 38. Origin of Doppler shifts in the channels of a radio interferometer.

as well as targets moving away from and toward the passive radar. Nevertheless, the radio interferometer selection method is highly interesting.

Let us now turn our attention to a certain similarity between this selection method and the Doppler shift in frequency method for selecting moving targets used in conventional radar work. In both cases the frequency of the output signal is proportional to target speed. This is not a chance similarity. The fact is that the radio interferometer actually separates information about the Doppler shift in the frequency of signals radiated by moving sources. Figure 38 will make this apparent. Each of the frequency components of the radiation from the target will experience Doppler shifts because the target is moving with respect to the radio interferometer. The magnitude of this Doppler shift at some frequency, f_r, within the limits of the receiver passband, will equal /89

$$F_{D1} = f_r(W/c)\sin\varphi_1 \text{ for the first channel}$$

and

$$F_{D2} = f_r(W/C)\sin\varphi_2 \text{ for the second channel.}$$

The difference in the Doppler shifts

$$\delta F = F_{D1} - F_{D2} = f_r\,(Wa)/(cD) = (aW)/(\lambda D).$$

is separated at the receiver output because of the displacement of the components F_{D1} and F_{D2}. But this difference is equal to the fill frequency of the output signal from the radio interferometer [see formula (50)].

The radio interferometer thus separates the difference in the Doppler frequencies of signals because the radio interferometer antennas are spatially separated. The greater the range to the target, the smaller this difference, because the angles φ, which determine the Doppler shifts in the channels, are smaller. Summarizing, we can say that by using the radio interferometer as our example we see that it is possible to extract additional information from thermal radio signals; in this particular case information on range and speed "buried" in the output signal can be used for target selection.

Let us now take up questions concerned with measuring range, and with range selection. This, unhappily, still is the most vulnerable part of passive radar work. With the exception of the radio interferometer method already described, the only method that can be cited is that of repeated bearing taking (the triangulation method), a method that in essence /90 reduces to taking simultaneous bearings on the target by antennas spatially separated and fixing the position of the target as the point of intersection of the bearings. It is obvious that this method is unacceptable for passive radars installed aboard ships and in aircraft.

The range selection method based on the use of "focused" antennas is finding some, albeit limited, application. The antennas used here can be special lens antennas, similar to short-focus optical lenses, for example. If an antenna-radiator is placed in one of the foci of an antenna such as this, and if a radiometer is connected to the antenna, radiation from small objects placed in the second focus of the antenna will be perceived best. Radiation from closer, and from more distant, objects will be out of focus in the radiator and, as a result will result in very much smaller increases in antenna temperature. Since the focal points are commensurate with antenna dimensions, the best this system can do is to select objects at distances of a few meters, and this us completely inadequate for the majority of location tasks. Accordingly, "focused" antennas are used exclusively in passive radar installations for scientific purposes, for studying plasma under laboratory conditions, for example.

Passive radar resolution, and methods for improvement. A serious drawback in passive radar sets is poorer resolution than that found in conventional radar sets. Such highly valuable methods as pulse compression and antenna "synthesization" have been developed in recent years for conventional radars, but these methods are not applicable to passive radars. Resort must be had to other approaches, therefore, in order to obtain high resolution in passive radar work. Here the methods developed in radio astronomy, where the problems of resolution are as critical as they are in passive radar work, are of interest. We already have pointed out the fact that resolution can be improved by replacing the conventional /91 single-channel passive radar with a radio interferometer. But while the method has been used successfully in radio astronomy, it requires complicated and lengthy decoding of the output signals, so its capabilities in passive radar work are limited. A second method, also borrowed from radio astronomy, is of great interest. This method provides high angular resolution without resorting to the use of large area antennas. Figure 39 shows the theory involved.

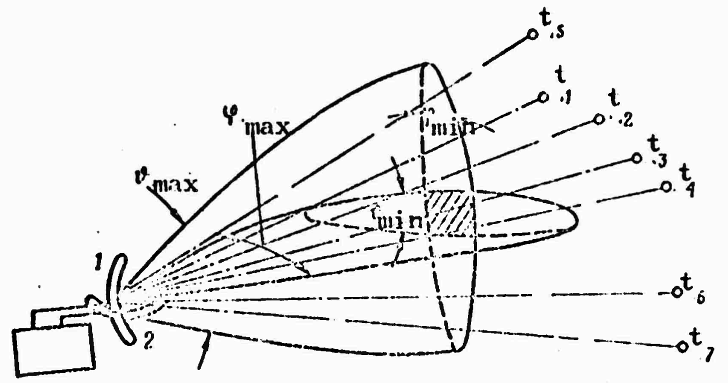


Figure 39. Passive radar with "compression" of antenna pattern.

As may be seen, the method is based on the use of two antennas with overlapping patterns. The antennas are connected to the inputs of a correlation radiometer. It is obvious that this system will react only to signals from targets that are in both patterns at the same time, that is, in the narrow "pencil-like" zone of pattern overlap. The advantage of the method is that the area of each antenna can be small because the pattern in one of the planes (vertical or horizontal) can be very wide without loss in resolution. If the antenna lengths are equal to l_1 and l_2, the resolution will be that found for a single-channel passive radar with an antenna with an area of $l_1 \times l_2$, which is tens, and even hundreds, of times greater than the total area of the two antennas used in the method described. Characteristic of the method is the crossing of two long antennas, so this system has been named the "Mill's cross," after the radio astronomer developer. /92

In concluding this chapter, a few words about the possibilities of improving the characteristics of passive radars that are related to the special features of thermal radio signals.

We initially spoke of the fact that the use of broad-band signals permits separating more information about targets. In this regard, we should point out that improvement in the resolution will increase the amount of information about targets. This is particularly true of scanning radars, for the better their resolution, the more detailed is the image obtained of the scanned zone.

It is convenient to use the example of the radio interferometer we already know about to discuss the principle involved in improving resolution. Let us consider the process involved in the reception of signals from sources occupying different positions in space (Figure 40). It is not hard to see that the best approach would be to receive signals from sources in a plane perpendicular to the base line of the interferometer and passing through the midpoint of the base line (the projection of this plane is shown in the figure by the straight line O-O). Sources located along this line are equidistant from the interferometer antennas, and the signals from each of these sources will arrive at the inputs to the correlation radiometer with different phase shifts and time delays.

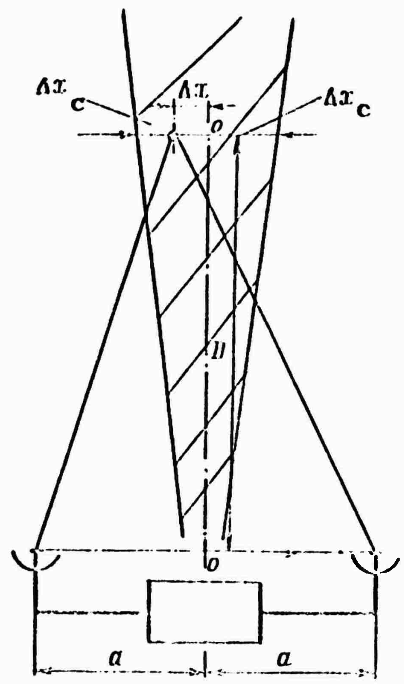


Figure 40. Improving resolution by using superbroadband signals.

If a source is displaced off axis O-O some distance x, the distances to the antennas will no longer be the same, and the distance difference will be

$$\Delta D = \sqrt{D^2 + (a + x)^2} - \sqrt{D^2 + (a - x)^2} \simeq \frac{2a\Delta x}{D}.$$

Accordingly, the signals will not arrive at the inputs simultaneously, but with shift Δt, equal to

$$\Delta t = \frac{\Delta D}{c} \simeq \frac{2a\Delta x}{Dc}.$$

When this shift exceeds the correlation interval, t_c, the radiometer's output signal is zero. Thus, the radio interferometer will receive signals only from targets the distance of which from the O-O axis does not exceed /93

$$\Delta x_c < \frac{Dct_c}{2a} \simeq \frac{Dc}{2a\Delta f}.$$

The live zone is a sector at longer distances ($D \gg 2a$), the angle of divergence of which is equal to

$$\alpha_c \simeq \frac{2\Delta x_c}{D} = \frac{c}{a\Delta f}.$$

This sector is a unique "antenna pattern," and can be made very narrow (for large Δf and 2a values). Provided is an increase in the angular resolution that is independent of the width of the radio interferometer antenna patterns.

4. The Use of Passive Radar

/94

The history of the development of passive radar covers a little over a decade, yet this comparatively short span of time has seen the development of passive radar theory, as well as the development of models of passive radars for the most varied of purposes. The main areas in which passive radar is used in foreign countries include:

detection, and plotting the coordinates of ground, surface, underwater, air, and space objects and targets;

cartography and terrain exploration;

solving marine and air-space navigation problems;

homing of various strike weapons;

physical investigations of substances and materials.

Moreover, the specific features of passive radar are such that tasks that cannot, in principle, be performed by conventional radar and infrared techniques, can be performed by this equipment.

These tasks are primarily those of:

all-weather astronavigation;

all-weather detection of sources of thermal energy;

noncontact measurement of the distribution of temperatures of objects, and study of their internal structures.

There are many other cases in which the use of radar and infrared equipment is, in principle, permissible, but passive radar is used instead because of its advantages. The combination of absolute secrecy /95
and the all-weather capability inherent in passive radar, for example, is extremely valuable for certain military uses, and the relative cheapness and reliability of passive radar equipment makes it so as well for the national economy.

Interest in the military uses of passive radar has increased in foreign countries in recent years. Foreign military experts are of the opinion that one can expect passive radar to be used in particular for homing in tactical guided missiles, for air reconnaissance, and for determining the condition of the atmosphere. The navigational use of passive radar is coming in for a great deal of attention in foreign countries. There is, in particular, information about the development of passive radar ground speed measurers, and of vertical-data transmitters. The feasibility of using passive radars to seek out zones of increased turbulence in the atmosphere that could pose danger in high-

speed aircraft is under review. The most widely used types today are the airborne passive radars for scanning the terrestrial surface, and the principle has been applied to radioastronavigation instruments, radio-sextants. Passive radars for other purposes are for the most part in the experimental stage of their development. A brief survey of those passive radars in use, as well as of the possible use that could be made of this type of equipment follows. It has been compiled from materials in the open Soviet and foreign press.

Passive radar for scanning ground and water surfaces. The first foreign experiments in obtaining images of the terrestrial surface with passive radar date back to the beginning of the 1950's, approximately, during which the equipment used was comparatively primitive. These experiments, conducted in England, used an 8 mm passive radar with a 12 m diameter parabolic antenna, and a radiometer with a sensitivity of about 10°/sec. The width of the antenna pattern was 0.5 degree, so the resolution at the site was 10 m when the aircraft carrying the passive radar was flying at an altitude of 1200 m.

This equipment was used to measure the apparent temperatures of different sections of the terrestrial surface, and it was established /96
that the apparent temperature of metal surfaces is a maximum of 100°K, and that water has an apparent temperature of 150°K. The apparent temperatures of open fields, meadows, forests, fields, and crops are approximately 280°K, and the apparent temperature of concrete, and of similar materials, is estimated to be 260°K. Figure 41 is a tracing of the output signal from a radiometer, combined with the plan of the section of the terrain overflown by an aircraft carrying a passive radar. The area was not scanned in this flight plan. The antenna was pointed straight down. The horizontal line on the plan is the trajectory along which the antenna pattern was moving, and since the horizontal scales of picture and tracing are the same, the signal strengths for the different sections of the terrain can be determined. The pips for the road and the canal can be seen quite clearly on the signal tracing, as can the difference in signal levels when flying over the forest and the field.

Successful experiments to obtain thermal radio images of terres- /97
trial and water surfaces were conducted in the United States in the early 1950's. The equipment used was in the 3.2, 1.25, and 0.8 cm bands and was based on conventional radars. The passive radars were installed in aircraft and lighter-than-air ships. It can be assumed that these radars used single-line scan, judging from the appearance of the published images. Pen recorders were used as indicators. The images were of poor quality, but they did establish that it was possible to observe shorelines (Figure 42), and that the radar had an all-weather capability.

Information about the addition to the arsenal of the U.S. Air Force of the AN/AAR-24 passive radar was published in 1961. This radar was said to make it possible to observe objects some 10 m in size from a flight altitude of 300 m, and large man-made and natural objects from /98
an altitude of several thousand meters.

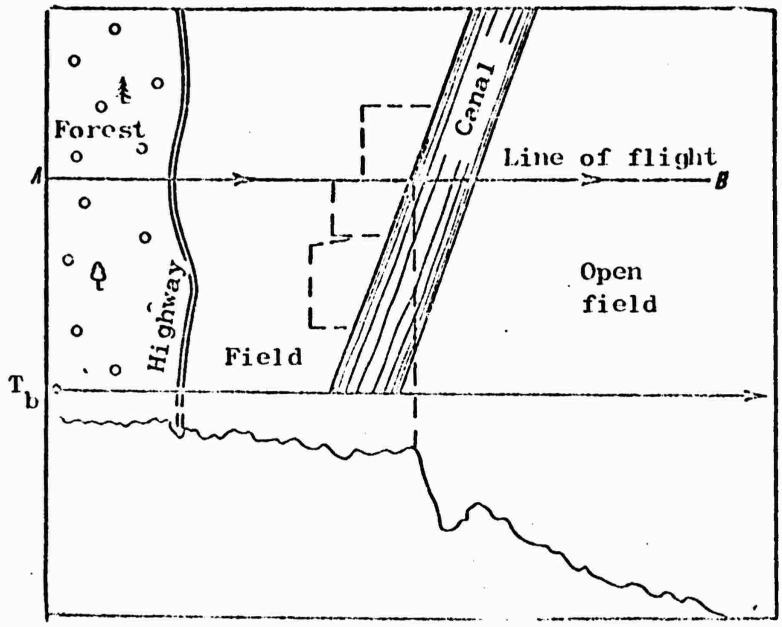


Figure 41. Tracing of radio brightness temperature along the line AB from an aircraft.

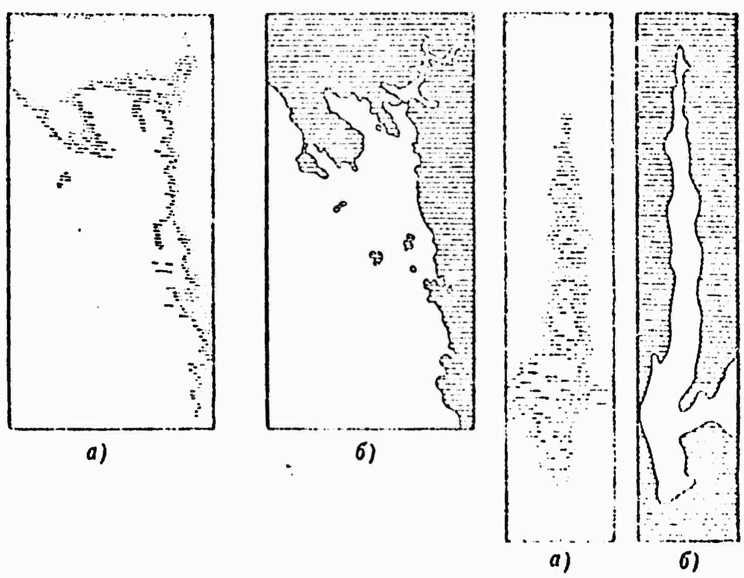


Figure 42. Thermal radio images of a shoreline (a) and charts of these same sections of the area (b).

The United States built better passive surveillance radars in the years that followed. Included, for example, is the AN/AAR-33, the first information on which appeared in the American press in the summer of 1966. The circuitry and design of this passive radar used the latest achievements of American passive radar techniques, so we shall take up the description of this passive radar in somewhat more detail than usual.

The AN/AAR-33 radar uses the single-line scanning principle discussed in the preceding chapter. There is but one receiving channel. The radiometer works in the 2 cm band, providing an overlap of a continuous band of frequencies from 13.5 to 16.5 GHz. The h-f passband thus exceeds 3 GHz, providing greater response.

The radiometer uses the modulation principle. An accurate pulse-type AGC is used to increase the accuracy with which the apparent temperature is measured. The carefully designed antenna accounts for the high performance characteristics of the radar. The antenna is a set of three identical parabolic reflectors mounted on a common shaft in such a way that the individual patterns are 120° apart. Scanning is accomplished by rotating the antenna system about its axis, which is tilted approximately 38.5° with respect to the horizontal plane (see Figure 43). The reflectors measure 65 x 91.5 cm. They are made of plastic, and are strengthened by a honeycomb design that uses a polymer material. The conducting coating, which contains silver, is applied to the working side of the reflectors. The width of the pattern of each antenna is 2.2 x 1.7°. The side lobe level is 25 dB.

The scanning rate can be adjusted from 3 to 12 beam passages per second. The antenna is installed on a gyro-stabilized platform that provides antenna stabilization in the horizontal plane accurate to 0.25°, thus improving the quality of the image obtained of the region.

/99

Figure 43. The An/AAR-33 antenna. a - general view. b - arrangement in a C-130 aircraft.

As scanning proceeds, each of the three sections of the antenna is connected in turn to the radiometer input through a low-loss antenna switch. /100

The switch design is based on that of a waveguide circulator, and the switch is electrically controlled. Maximum switching time is 50 μsec.

This same switch is used for the input of the AGC reference signal. Switch operation and antenna rotation are so synchronized that a section with a pattern scanning the area from -55° to +55° from the vertical is always connected to the receiver input.

The switch, when the operating cycle for each of the sections is completed, connects the radiometer input to the standard noise signal source for calibration and forming the AGC pulse. This condition is maintained for 1/36 of the antenna rotation period, after which the next antenna section, the pattern of which has by this time reached the limit of the surveillance zone, is connected to the radiometer input. The complete scanning cycle, expressed in degrees of angle of rotation of the antenna, thus has the following form:

scanning by 1st section - 110°, calibration 10°;

scanning by 2nd section - 110°, calibration 10°;

scanning by 3rd section - 110°, calibration 10°.

The antenna drive is hydraulic.

The passive radar has three units. The antenna unit, in addition to the antenna, contains the switch, the radiometer head with all the h-f stages, the detector, and the l-f preamplifier. The antenna unit is installed in the upper part of the C-130 aircraft's cargo hatch (see Figure 43). The control signal generator unit contains the final stages of the radiometer, the synchronization stages, the signal amplifiers that produce the antenna stabilization signals, and the hydraulic installation for supplying the antenna drive mechanism. This unit is mounted alongside the antenna unit. The AGC circuitry, the computer into which navigation data are fed, and the stages for amplifying the output signals from the radiometer that are used when the recorders are in operation, are installed in the set's control console.

The radar uses two recorders. One, the plan recorder, records /101
the thermal radio map, the other, the amplitude recorder, makes an accurate recording of the apparent temperature along the scanning line. In addition, the signal trace is fed into a special magnetic recorder. The AN/AAR-33 will detect objects, the radio brightness temperatures of which differs but little from the radio brightness temperatures of the background. It is pointed out, in particular, that if the target fills the antenna pattern's main lobe completely, all that is needed to detect the target is a radio brightness contrast with the background of about 1.75°K. The accuracy with which absolute values of radio brightness temperatures can be measured is ±5°K. Figure 44 shows the images of different sections of a terrain obtained by the AN/AAR-33 passive radar. The pictures were obtained from an altitude of 360 m, which provides terrain coverage approximately 1,300 m wide. The dark sites on the pictures are sections with higher apparent temperatures. The light sites are metal and concrete objects that are "colder" than the terrestrial surface. Note the fine detail of the images. The right-hand portions of the upper, and succeeding, films clearly show the runways and taxi- /102
ways of an airfield. A sharp vertical road marker can be seen. Readily

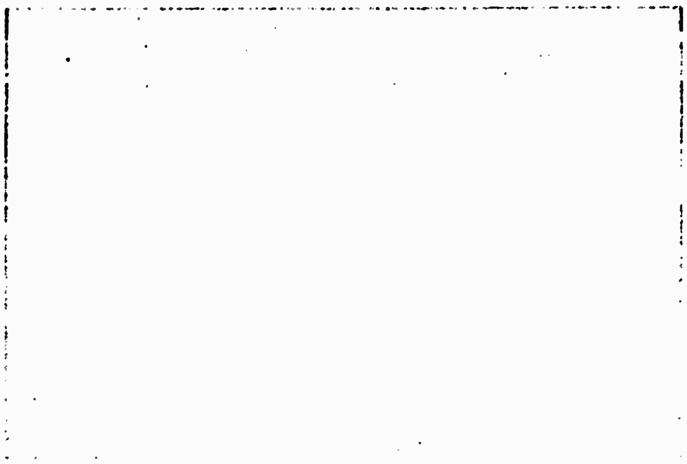


Figure 44. Images of terrain obtained by the AN/AAR-33 passive radar.

recognizable in the second film alongside the road is the outline characteristic of a small settlement. A great many comparatively small details can be seen on the third film, corresponding to a section of an agricultural area. The fourth film depicts a port area. The coast, the port installations, and individual ships can be seen quite well.

We should point out that the principal purpose of the AN/AAR-33 passive radar is to monitor the ice situation in the interests of navigational safety, and not to map the terrestrial surface.

However, the American experts suggest that it be used to solve certain purely military problems, such as reconnaissance of a coast in areas in which amphibious landings will be made, for example.

They are of the opinion that airborne passive radar for scanning the terrestrial surface can be used for battlefield reconnaissance, target designation, and mapping, as well as for detecting and delimiting forest fires. Success in using passive radar to detect the portions of the forest that were burning through dense smoke cover that neither light nor infrared rays could penetrate was attained while fighting big forest fires in the Los Angeles area.

Passive radars also can be used to scan the earth from spacecraft. It is in this area that such positive qualities of passive radars as economy and reliability come to the fore. The drawback in the use of passive radar, poor resolution, can be overcome by using antennas with larger areas, including folding and inflatable ones.

The United States developed a 2 cm passive radar that was installed in the Nimbus D satellite. This satellite, since it is in a polar orbit at an altitude of about 1,000 km, can see the entire surface of the globe successively.

It is reported that this radar can measure the apparent temperature of the terrestrial surface accurate to 1°k, so it may be assumed that the radar's radiometer is similar to the solid-state, highly sensitive, radiometers described in chapter 2. The passive radar carried by the

Nimbus satellite uses a flat waveguide-slot antenna with single-line electrical scanning. The principal characteristics of this antenna are: /103

working frequency 19.35 GHz;

scanning angle ±50°;

pattern width, half power:

within a scanning angle of ±30° - maximum 3°;

within the limit of full scan - maximum 4°;

antenna efficiency 0.74;

scattering factor 0.08-0.12 (depending on scanning angle);

dimensions 45 x 45 x 7.5 cm;

weight about 3.5 kg.

An interesting feature of the passive radar is the use of discrete scan. The beam does not move smoothly within the limits of the full deflection angle, but rather in steps, successively taking up 39 fixed positions. The developers think discrete scan should simplify coupling the passive radar to the telemetry equipment and make it easier to perform the digital processing of the data obtained.

The antenna is designed with 49 waveguide segments connected to the feeder waveguide. Each segment has 36 slots, which are elementary antennas. Electrical scan is accomplished with the aid of controlled ferrite phase shifters installed in the waveguide segment. The power requirement for controlling the phase shifters is a maximum of 9.5 watts.

Passive radar has quite an important place in American plans for setting up systems that will perform reconnaissance functions from space. The foreign press indicates that these systems will use active and passive instruments that will cover the gamut of electromagnetic radiation, from radio to ultraviolet waves.

It has been reported, for example, that the United States wants to develop a 4 mm passive radar with an angular resolution of about 20" for installation in an artificial earth satellite by 1970. The antenna for this radar will have a linear dimension of about 6 m. We should /104
point out that the energy relationships for a passive radar for scanning the terrestrial surface from space vehicles are only slightly poorer than those for comparatively low-altitude passive radars. Actually, passive radars such as these operate in a mode for measuring the thermal radio relief, and as has been pointed out in chapter 3, in this mode the antenna temperature can be reduced by increase in range only as a result of atmospheric attenuation, the influence of which can be reduced to a minimum by selecting the band for the passive radar accordingly.

Foreign countries attach a great deal of importance to the use of airborne and water surface craft passive radars for sea surface search. Sections of the land fronting on the water have quite a thermal radio contrast (100-150°K), so it is possible to detect the coast, islands, and the like, at quite long ranges when the sea is the background.

Ships too can be detected quite well when the sea is the background. It has been established experimentally that ships observed at short ranges will have both positive and negative contrasts between different parts of the particular ship when the angular dimensions of the ship are greater than those of the passive radar antenna pattern. This phenomenon obviously is associated with heterogeneity of the materials of which the ship's superstructure is built, and this could make it possible to arrive at a decision as to the type of ship observed.

Passive radar can be used to detect the wake, the temperature of which is several degrees higher than the temperature of the surrounding water, as well as the ship itself. Wake observations, in turn, make it possible to determine ship's course and speed. The wake is not confined solely to surface ships. Submerged submarines too leave a weak surface thermal trace. The United States has developed a special airborne passive radar for detecting submerged submarines by this trace. The highly sensitive correlation radiometer in this passive radar has a quantum mechanical h-f amplifier. One of the journal articles asserts that this passive radar solves the problem of 24-hour, all-weather detection of submarines from aircraft in zones with an area in the thousands of square kilometers.

Passive radar has been extremely effective in searching the sea /105
surface during ice reconnaissance and in detecting icebergs. As is known, ice is a good absorber in the centimeter and millimeter bands, and it is this fact that makes it very difficult to detect ice with active radars. Yet this very fact is what helps detect ice with passive radar equipment. The first experiments conducted by the United States used a very simple 3 cm passive radar with a fixed 60 cm parabolic antenna. The radiometer was one of the modulation type, and the receiver was a conventional superheterodyne with a passband of 5 MHz. This radar provided reliable detection of icebergs under cloudy conditions at ranges up to 600 m (Figure 45). Characteristic is the fact that the signal from the iceberg, which exceeded the fluctuation threshold of
sensitivity by a factor of almost 16, was observed at the radiometer /106
output, yet this same iceberg did not show up on the passive surveillance radar scope.

The AN/AAR-33 passive radar has much greater capabilities for detecting icebergs, for it can detect ice protruding just a few centimeters above the surface of the water. Moreover, currents can be traced on the images of the water surface if the currents carry ice particles. So it follows that radars that can search the sea surface can be very useful for a variety of hydrological studies. It should be possible to use passive radar to determine sea conditions, and to study the temperature regime of the sea surface, for example.

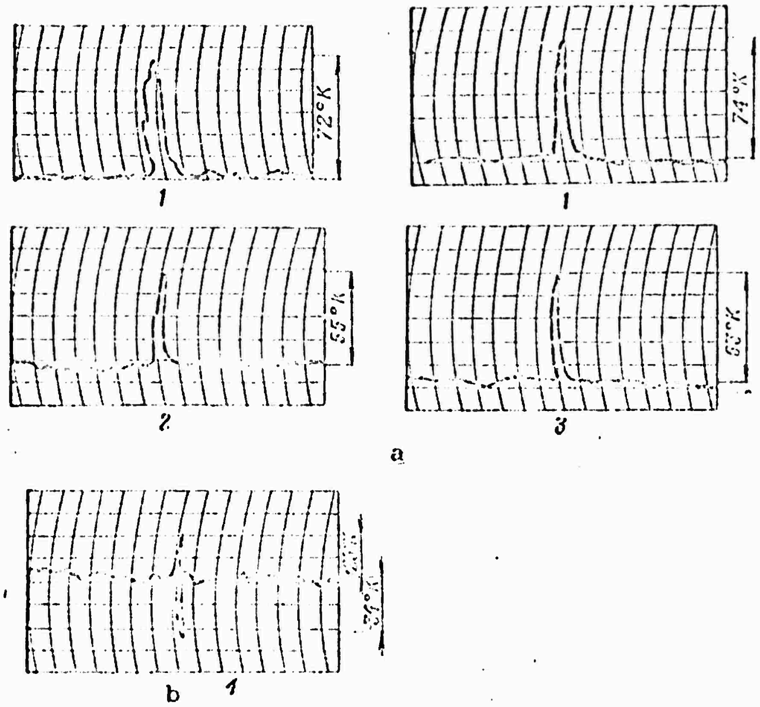


Figure 45. Iceberg and ship pips on a passive radar recorder tape. 1 - altitude 150 m, flight below the clouds; 2 - altitude 800 m, flight above the clouds; 3 - altitude 150 m, small iceberg; 4 - pip for small ship.

A group of Soviet scientists successfully performed experimental measurements of the surface of the Caspian Sea with a centimeter band passive radar in November-December 1964. The original procedure they used yielded highly accurate measurements. Temperature values thus measured were within 1.5-2.5°C of true values.

In concluding this section, let us not forget foreign developments in passive radar with better resolution. Recent research has shown that waves in the 3 mm band undergo only slight attenuation when propagated within the limits of the earth's atmosphere under almost any kind of meteorological conditions (with the exception of rainy areas), so some firms have begun to develop radiometric equipment in this band. An experimental model of a 3 mm passive radar was tested (working frequency 94 GHz) and provided much sharper terrain images than those provided by centimeter band equipment. This is completely in accordance with the laws involved because passive radar resolution is better by a factor of 10 in the 3 mm band than it is in the 3 cm band (antenna dimensions being equal). Figure 46b is a thermal radio image of a lake surrounded by mountains and forests, obtained with just such a passive radar. Figure 46a is a photograph of the same area. Details of the image are quite good. The American press emphasizes the fact that the quality of the image will not deteriorate, even under very dense fog conditions, /107
when optical and IR equipments are completely useless.

We should point out that the image in Figure 46b was obtained with

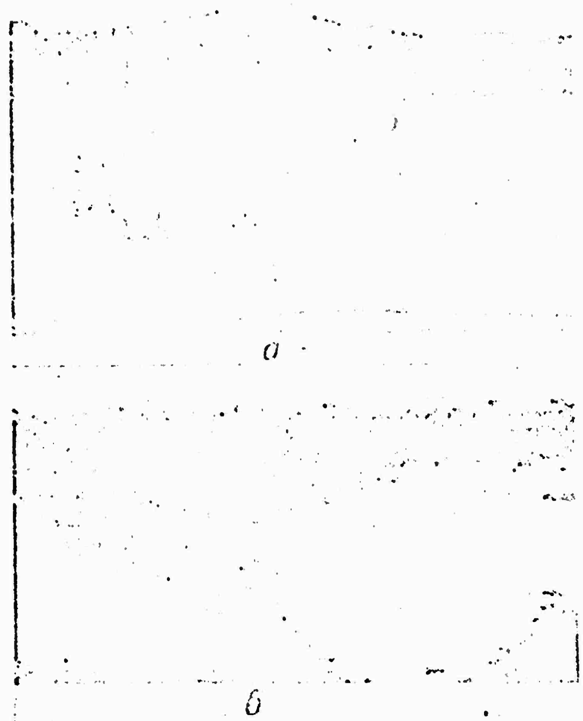


Figure 46. Mountain, lake, and forest. a - photograph; b - thermal radio image on 94 GHz.

a single-channel radiometer, the signal from which was recorded on magnetic film and was, after amplitude analysis, used to form a two-dimensional picture of the radio brightness temperature. Development of a 3 mm band multichannel radiometer is in progress. Specifically, the feasibility of designing a mosaic receiver system consisting of 100 barrier diodes (Shottky diodes) is under study. The United States is developing /108
passive radar equipment working on 140 and 250 GHz, in order to obtain even better resolution.

So the frequency band used for passive radar has come very close to the submillimeter. But this does not mean that the longer wave bands will be neglected, however. There are reports of the development of a 30 cm band passive radar, and it also is known that the United States recently conducted ground tests with a meter band passive radar. It is interesting to point out that in the meter band the radio brightness temperatures of cities have turned out to be unusually high, as high as 20,000°K. This can be explained by the hign spectral density of the different types of industrial noise, the sources of which are concentrated in cities.

Use of Passive Radar for Navigational Purposes

Foreign specialists are of the opinion that passive radar can be an effective tool for use in navigation, by sea or in the air. Passive radars can be used, for example, to plot the coordinates of ships and aircraft, to measure speed, for dead reckoning, to prevent collisons

with obstacles, for landing aircraft in bad weather, and the like.

The principal features of passive radars designed to solve various navigational problems are reviewed in brief in what follows.

Radio sextants. A radio sextant is a passive radar designed to make an accurate plot of the angular coordinates of extraterritorial sources of radio radiation. The simultaneous measurement of the angular coordinates of several (at least two) sources by conventional astronavigation methods provides the latitude and longitude of the point at which the radio sextant is located. The altitude angle of the source, and its course angle, are selected as the angular coordinates to be measured.

Modern radio sextants work on the principle of automatic tracking in terms of angular coordinates, and all radio sextants described in the literature use conical scanning. /109

The functional arrangement of the simplest radio sextant with conical scanning is similar to the arrangement of the passive tracking radar described above.

The accuracy of the radio sextant is determined by the influence of fluctuating and dynamic errors caused by the relative angular displacement of the object on which the radio sextant is mounted, and of the source, the bearing of which is being taken.

The most significant component of the dynamic error usually is the object's own angular motion.

The angular rate of roll of small ships, for example, can be tens of degrees per second, and the angular rate of rotation of the vertical can be in units of minutes of arc per second, for high-speed objects. The angular rate of the earth's rotation is equal to 15 minutes of arc per minute.

An accurate plot requires measurements of angular coordinates, the error in which should be a maximum of a fraction of a minute, so the time constant cannot be large where such high angular rates are involved.

However, the faster components of the angular rate have absolutely no connection with the displacement of the earth with respect to the source on which the bearing is being taken, nor with the coordinates of the object on the earth's surface. So another device can be used to take them into consideration, using the radio sextant for the slow components of the relative angular rate attributable to the errors in the device indicated, as well as by the mutual displacement in space of the earth, and the source on which the bearing is being taken.

If the radio sextant antenna is mounted on a gyrostabilized platform, this platform, maintaining its position in space, "subtracts" the rapid components from the antenna's relative angular rate, thus creating conditions for a longer averaging of the output voltage from the radiometer. In this case, the upper limit of the l-f filter time constant

is, for all practical purposes, determined by the angular rate of the parasitic drift of the platform, which can be tens of degrees per hour, as well as the time for the transient processes during target lock-on - locking onto the source of the radiation. /110

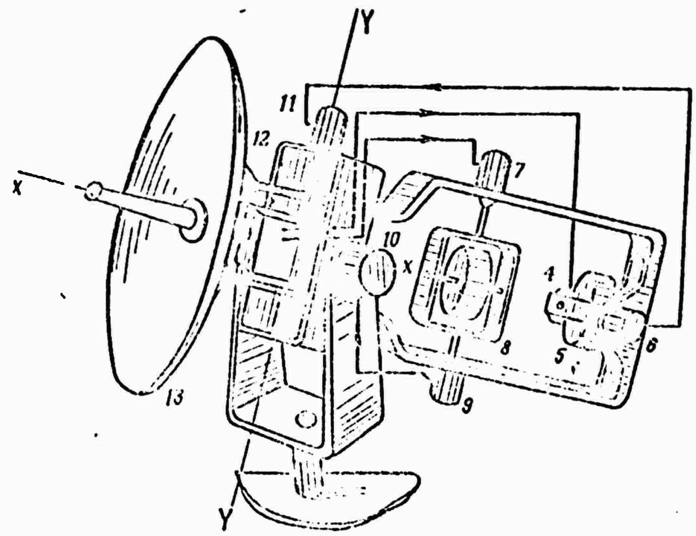


Figure 47. The operating principle of the gyrostabilized radio sextant.

Feedback is used in the system to compensate for drift in the gyro-stabilized platform. Drift creates an angular error which is measured by the radio sextant and used to correct the platform's gyroscopes. It is more convenient to design the installation so the sextant antenna will be stabilized with respect to a line connecting the center of the antenna with the center of the source on which the bearing is being taken, rather than with respect to the vertical. Figure 47 illustrates the operating principle of a radio sextant with this type of gyrostabilization. Deflection of the source from the equisignal direction in the horizontal plane will cause an error voltage to appear at the phase detector output. This voltage is supplied to the torque motor, 4, in the azimuth channel, 5. The gyroscope begins to precess around an axis parallel to the Y axis, taking along the antenna base, 12, to which the antenna, 13, is attached. The equisignal zone once again attempts to line up with the direction to the source on which the bearing is being taken. Once lined up, the error signal at the phase detector output disappears, gyroscope precession ceases, and so too does the motion of the antenna base. /111

Let us now suppose that an external disturbing torque acts on the object on which the radio sextant is mounted, trying to displace the equisignal zone into the plane of the azimuth. This torque causes the gyroscope, 5, to precess and this is accompanied by rotation of the gimbal in which it is suspended relative to the antenna base. The gyroscope gimbal is connected to the shaft of a selsyn transmitter, 6, the amplified output voltage of which is supplied to motor 11. The torque developed by the motor, 11, is opposite in direction to that of the disturbing torque, and greater than it in magnitude. The result is to keep

the angular position of the antenna unchanged with respect to the direction to the source. An error in the vertical plane is handled in exactly the same way. This part of the circuit uses gyroscope 8, torque motor 7, selsyn transmitter 9, and power unloading motor 10. The drawback in the simplest radio sextant is that the power gyroscopes used as the stabilizing elements are quite heavy and large. This is why a somewhat different form of stabilization is used in practice (Figure 48). This arrangement controls the position of the antenna with a special power drive, and the kinematic elements used for tracking and stabilization are separate.

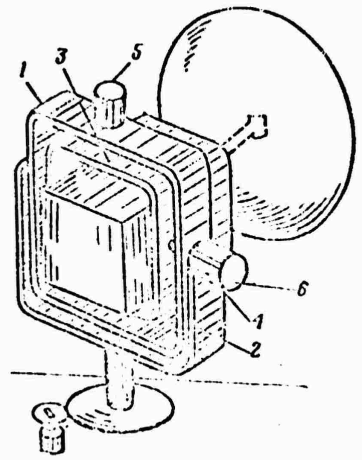


Figure 48. A gyrostabilized radio sextant.

As may be seen from Figure 48, the antenna suspension system consists of two suspensions (the inner, 1, and the outer, 2), each of which consists of two gimbals rotating around mutually perpendicular axes. The inner suspension is stabilized and functions only in the event of the appearance of external disturbing torques, and does so in exactly the same way as that described above for the simplest gyrostabilized sextant. /112
The power gyroscopes in the tracking system have been replaced by a power drive. The signals supplied to the power drive input come from contact transmitters when the gyroscopes process as a result of deflection of the axis of the equisignal zone from the direction to the heavenly body in question. The outer gimbal drive is, in addition, connected to the compass transmitter, so the sextant will function normally when the ship is maneuvering.

Errors in measuring angular coordinates with the gyrostabilized sextant have a two-fold dependence on the time constant. The error in the bearing part of the instrument decreases with increase in τ on the one hand, and error caused by drift of the gyroscopes increases with increase in τ on the other.

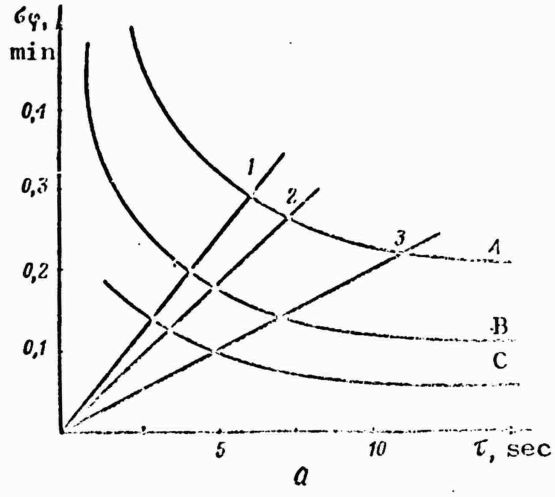
Figure 49 shows the curves for these errors as a function of τ for one of the models of foreign 2 cm radio sextants.

The first radio sextants, built with comparatively low response radiometers, were designed for sun work only. Combination Sun-Moon radio sextants subsequently were developed in order to increase the time of possible use of radio sextants, and attempts even were made to design radio sextants working on radiation from discrete sources. The

latter task was greatly complicated by the low intensity of the radio radiation from discrete sources, the most powerful of which, Cassiopeia, emits radiation in the centimeter band that is less than that from the Moon by a factor in the hundreds. Accordingly, the rise in the antenna temperature when working with discrete sources is extremely low (less than 0.01°K), and is at the limit of the capabilities of modern radiometric apparatus.

And in this connection, errors in measuring the coordinates of discrete sources are high.

A 4 cm radio sextant, for example, found the altitude of Cassiopeia with an error of 40'. The error in plotting the angular coordinates of the moon with this same sextant was 0.25'. /113



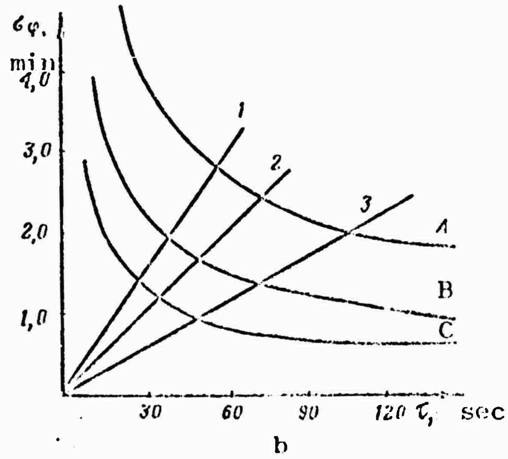


Figure 49. Angular radio sextant errors as a function of the l-f filter time constant. a - working with the Sun; b - working with the Moon. Gyroscope drift: 1 - 3°/hr; 2 - 2°/hr; 3 - 1°/hr. Antenna diameter: A - 57.5 cm; B - 70 cm; C - 91 cm.

According to the information in the foreign press, radio sextants are widely used in the navy and in aviation. The table lists data on some foreign shipboard and airborne radio sextants.

Foreign submarines also use radio sextants. Modern submarines have great endurance and can remain submerged for thousands of miles. Navigation is by dead reckoning, and characteristic of this type of navigation is a temporal accumulation of errors. This is what has posed the task of developing all-weather equipment for position fixing that does not require the submarine to surface. To this end foreign countries have developed special periscope radio sextants, the antenna systems and h-f section of which are installed in retractable domes. So-called float radio sextants also were designed for submarines. The antenna and the h-f head of the float sextant are installed in a special airtight float-dome that is towed along the surface by the submarine, which is running submerged. The periscope radio sextant is part of the equipment for the self-contained SINS navigation system installed in American nuclear submarines. /114

The first models of airborne radio sextants appeared in the United States in 1953. They were solar radio sextants, designated the AN/SAN-25, operating in the 1.9 cm band. The sextant used a round parabolic antenna with a diameter of 60 cm. Weight of the units comprising the instrument was 45 kg (not including the gyrostabilizer). Radio sextants in the 8 mm band subsequently were developed for high-altitude aircraft. The mockup of one such radio sextant designed in the United States has a 38 cm diameter antenna and can measure the sun's angular coordinates with an error of about 1'.

Further development of the idea of a gyrostabilized radio sextant led to the designing of unified radioastroinertial navigation complexes. Examples of these complexes are the homing system for the American intercontinental aircraft-missile known as Snark, and the SINS system already mentioned. Also known is the fact that the United States has developed radioastronomy systems for controlling the launching of missiles from surface warships. The system works in the 4 cm band, and can receive signals from 12 discrete sources. It has been proposed that similar systems be installed at United States missile test ranges. /115

American specialists are of the opinion that radio sextants also can be used for navigation by radio radiation from satellites, as well as for the needs of space navigation, topography, and geodesy.

Data in the foreign press suggest that future improvements in radio sextants will be along the following lines:

1. the development of low-noise radiometers using quantum mechanical and parametric amplifiers;

2. the development of millimeter band radio sextants.

<u>Passive radars for aircraft navigation</u>. As we have pointed out above, it is impossible to make a direct measurement of the Doppler shift

CHARACTERISTICS OF FOREIGN SHIPBOARD AND AIRBORNE RADIO SEXTANTS

Radio sextant type and designation	Manufacturing country	Year	Source of radio radiation	Band, cm	Antenna diameter, cm	Mean-square-error in measurement (minutes of arc)
Shipboard, AN/SAN-1	USA	1951	Sun	1.96	75	1.9
Shipboard, AN/SRN-4	USA	1958	Sun, Moon	1.8	150	0.25
Mockup of an airborne radio sextant	USA	-	Sun	millimeter	38	1.0
Airborne, AN/SAN-25	USA	1953	Sun	1.9	60	2.0
Airborne radio sextant	England	-	Sun, Moon	millimeter	30	-

in own thermal radio radiation by using a single-channel passive radar. Therefore, the proposal was made at an early stage in the development of passive radar that in order to determine track speed the Doppler shifts in natural radio radiations from nonterrestrial sources reflected from the terrestrial surface be measured, or that the spectrum of the 1-f signal in terms of the scanning rate be used. /116

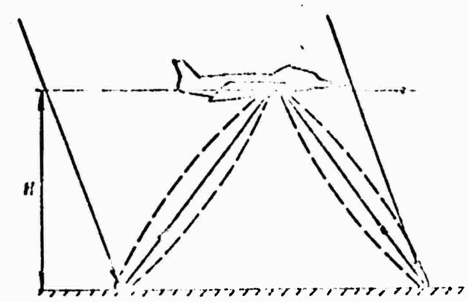


Figure 50. Measurement of ground speed by Doppler shifts in intensifying radiations.

The first method of measuring ground speed involves the installation on the aircraft of two beam antennas, the patterns of which are oriented down-forward and down-aft (Figure 50). The antennas receive radio radiation from the sun, or cosmic radio radiation reflected by the terrestrial surface. Since these signals are the same "intensifying" signal with different Doppler shifts, the difference Doppler shift, which is proportional to the aircraft's ground speed, can be isolated.

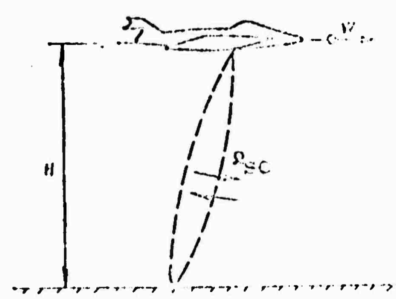


Figure 51. Measurement of ground speed by the spectral analysis of output signals.

The second method for measuring ground speed has the pattern oscillate back and forth in the vertical plane at a strictly constant angular rate (Figure 51). In this scanning method search is at the rate $W + \Omega_{sc} H$ when the antenna pattern is moving forward, and at the rate $W - \Omega_{sc} H$ when the pattern is moving aft.

The spectra of antenna temperatures too will differ when the patterns are moving forward and aft, and this difference will depend on the magnitude of the ground speed.

The possible methods for measuring ground speed described have been simplified on the assumption that only one component of the ground speed vector need be measured. Determination of the second component requires an increase in the number of antennas, just as is the case in radar (Doppler) ground speed measurers. /117

There were reports in the foreign press in 1966, to the effect that the United States was looking into the feasibility of using passive radar to provide navigational support to aircraft and helicopters of Army aviation. As these reports pointed out, it was believed to be completely feasible to develop passive radars to automatically track ground landmarks, as well as passive radars for measuring speed and altitude. One article describes a speed measuring method based on using a two-channel passive radar with a correlation receiver.

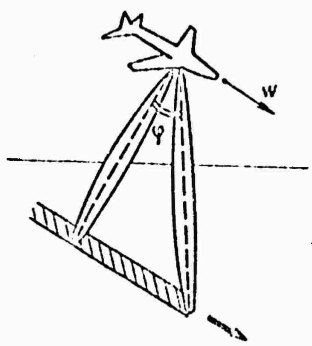


Figure 52. Principle involved in measuring ground speed using two-channel reception.

The antenna patterns associated with each of the channels are oriented as shown in Figure 52. If both patterns lie in the vertical plane passing through the ground speed vector, changes in radio brightness temperatures recorded by the after channel will have a temporal lag with respect to the changes recorded by the forward channel of

$$\tau_a = H \sin \varphi / W.$$

Since angle φ is known, the relationship between altitude and speed can be determined by determining the lag time with a correlation receiver and an adjustable delay line. Flight speed can be found when the altitude is known. /118

Figure 53 is the functional diagram of a passive radar for measuring ground speed.

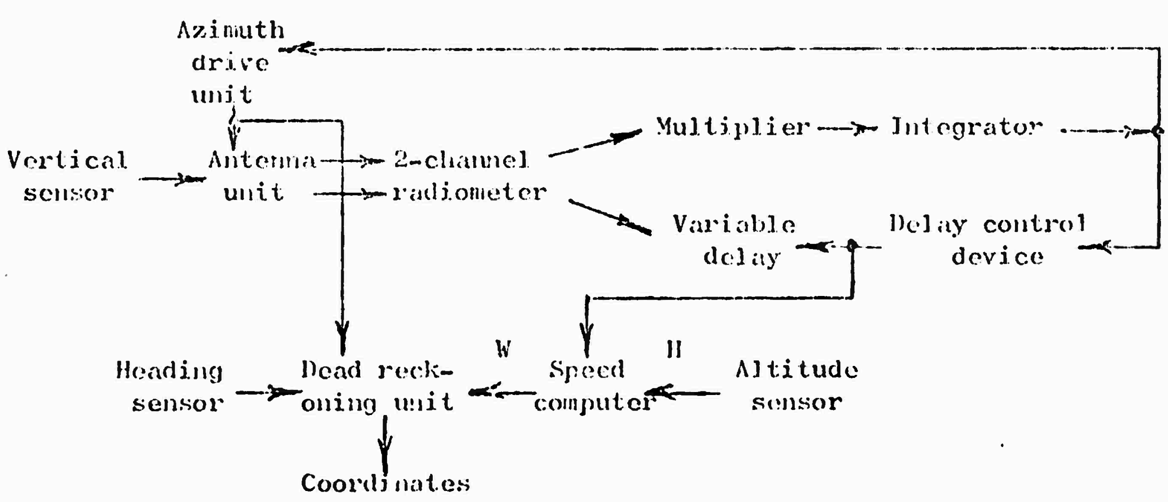


Figure 53. Functional diagram of a two-channel ground speed measurer.

Passive radar techniques also can be used for spacecraft navigation. Of greatest interest here is the design of thermal radio horizon sensors for orienting spacecraft in orbital flight. As distinguished from the presently used IR horizon sensors, the thermal radio sensors are not affected by the noise in the reflection of solar radiation from the clouds covering the earth, so can provide greater below the horizon tracking accuracy. /119

Two types of such sensors have now been developed, follow-up and scanning. The drop in the radio brightness temperature between earth and sky causes follow-up sensors to generate a signal that reverses antenna direction. This produces oscillating antenna patterns in the vicinity of the horizon. Scanning sensors measure the time-dependent position of radio brightness temperature pulses that occur as the antenna pattern passes through the "sky-earth-sky" line and form the corresponding error signals. This is the principle underlying passive radars designed to warn the aircraft that it is in danger of hitting various obstacles. A signal, the phase of which depends on the apparent angle of the horizon, is formed when the forward hemisphere is scanned in the vertical plane by a narrow, needle beam. The horizon angle, and its rate of change, thus can be determined. Flight safety is guaranteed when these magnitudes are kept within prescribed limits (Figure 54).

Figure 54. Passive radar operating principle ensuring overfliglt of obstacles.

The United States is studying the feasibility of using passive radars in landing systems, and in particular for setting aircraft down on a runway. It has been established that concrete runways can be seen reliably by a 3 cm passive radar, even in heavy rain (25.4 mm/hr). It is suggested that "cold" or "hot" markers be installed along the edges of a runway to improve passive radar visibility. /120

Detection of Air-Space Objects By Passive Radar. Use of Passive Radar for Missile Homing.

The first reports of the development of passive radar for air space surveillance appeared in the foreign press in 1959. Under development abroad today are passive radar equipments for detecting space, as well as air, objects. The United States, for example, is engaged in research in the feasibility of using passive radar to detect ballistic missile warheads at the time they enter the atmosphere. As is known, a body entering the atmosphere at high speed will heat up very greatly. A high-temperature plasma layer forms on the surfaces of such bodies, and this causes intensive thermal radio radiation, while simultaneously reducing radar contrast. The jet engines installed in modern high-speed aircraft are powerful sources of radio radiation. The aerodynamic heating of the

skins of high-speed aircraft also contributes to increasing thermal radio radiation. These are the principles that give American experts reason to believe it is feasible to use passive radars for homing air-to-air missiles. The passive radar coordinates of homing missiles have two great advantages as compared to those obtained using conventional radar. One is the high degree of stability when working at short ranges (because the harmful effect of "scintillation" is absent). The other is complete secrecy. It is this latter advantage that is particularly important because it deprives the enemy of the possibility of generating effective spot jamming.

And it is considered that the possibilities for using passive radar in air-to-surface missile homing systems are good. The relative ineffectiveness of existing guidance systems has forced the American Army to begin the development of a series of guidance systems that utilize new /121
physical principles. The work along these lines has been combined into a special program, 679A, one of the main purposes of which is to develop passive radar for air-to-surface missile guidance systems. The United States Navy also has placed an order for a passive radar guidance system, the final section of which will operate in the millimeter band. The antimissile defense forces in the United States are showing an interest in passive radar guidance systems, and they are of the opinion that miniature target coordinates, acting on the passive principle, are needed for antimissile defense systems.

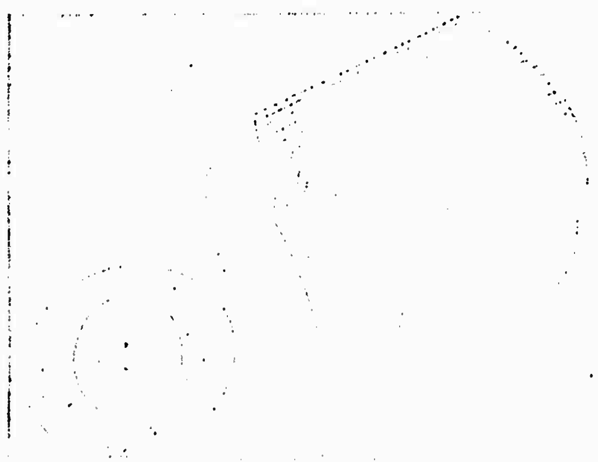


Figure 55. Construction of an antenna for a passive radar homing head.

A number of American firms already have developed the basic components for passive radar guidance systems. Spies General, for example, has produced a SHF head designed for use in an air-to-surface passive radar system. The head contains a multibeam horn-lens antenna that is well within the limits of the missile dimensions. One lens, in the form of a cylindrical ring (Figure 55), forms all beams. The head can be very simply butted to the adjacent missile compartments because the outside diameter of the lens is equal to the diameter of the missile body. /122

A cylindrical unit of horn radiators, located inside the lens, is used to form the individual patterns. The horn radiator rulers are

positioned along the generatrices of the unit's cylindrical surface. The antenna uses a total of 60 such rulers, each of which contains 24 radiators. Circular scanning is accomplished by switching the feeder flanges of the waveguides for the rulers. Scanning in the plane of the generatrix is accomplished by introducing phase shifts between the horns of like rulers.

Also suggested is the use of passive radars to detect satellites and nuclear bursts in space. Calculations made using the formulas cited in chapter 3 show that the range at which air-space targets can be detected can vary from a few kilometers to several tens, and even hundreds, of kilometers.

Scientific Applications of Passive Radar

Passive radar (radiometric) methods are widely used in plasma research to determine radiation intensity, electron density, and other plasma parameters.

Passive radar has been in use for several years now in physical research in the atmosphere. Study of thermal radio radiation from the atmosphere, and of absorption in the atmosphere of extraterrestrial radiation, will yield data on the distribution of temperatures in the air masses, on the nature of turbulence in the atmosphere, on the concentration of water vapors, and so on. Use of passive radar in meteorology will make for better research in the structure of cloudiness, storm fronts, and the different types of precipitation. There is information about the successful use of passive radar at some of the meteorological stations in the United States.

Some time should be taken to discuss, in particular, the use of passive radar in geophysics and hydrology. Foreign countries began to use passive radar to research terrestrial rocks several years ago. The effectiveness of passive radar as a geophysical tool can be explained /123 by the fact that the thermal radio picture of the terrestrial surface can "tell" the scientists the physical temperature of the terrestrial surface, as well as a great deal about many of its other features, including soil properties and moisture, and so on. Highly important is the fact that passive radar methods can be used to study the terrestrial surface in the winter time, particularly to determine the thickness of the snow and ice coverings of different sections of the land and water areas.

Passive radar can be used in hydrological research to determine water temperature and the directions of current flows, as well as to determine sea state.

Passive radar has made quite a contribution to the study of the physical structure of the atmosphere. Here it is Soviet scientists who have played a leading role. In recent years they have made a series of studies of thermal radio radiation from the atmosphere in the centimeter and millimeter bands.

In conclusion, let us pause to consider one intriguing prospect of the use of passive radar in physicotechnical research. There are many

branche of science and engineering where a real problem is that of measuring the distribution of temperatures over the interior volume of various physical bodies. This problem usually is resolved by installing contact temperature sensors at the points where measurements must be made. There are serious inconveniences in this solution in the majority of cases, and there are times when it is absolutely impossible to use this approach. The use of noncontact temperature measurers in the IR band is precluded because of the heavy attenuation of infrared radiation in the majority of solid bodies.

However, many solid bodies have low conductivity, so do not greatly attenuate radiation at radio frequencies. Therefore, thermal radio radiation emanating from deep within these boiies is propagated beyond the limits of the bodies, and we can determine the temperatures in the various sections of the body under study by measuring radiation intensity. Needless to say, this does require the use of special antennas that can separate the components emanating from strictly localized sections of the space from the total emission. /124

The potentials of passive radar are by no means limited to those discussed above. There are those in foreign countries who believe that passive radar can be used to advantage in secret communication systems, in warning systems for guarded territories, and in solving many other technical problems.

Comparative Features of Passive Radar, Conventional Radar, and Infrared Equipment in Brief

We have familiarized ourselves with the physical bases of passive radar, and with the elements involved in its engineering. But if we are to judge the feasibility of using passive radar for some one particular purpose, we must have a good understanding of the advantages and disadvantages of passive radar as compared with conventional radar and infrared direction finding.

Presented in brief in what follows are comparative features of the main properties of passive radar, conventional radar, and infrared equipment that can be helpful in evaluating the feasibility of using passive radar to perform specific tasks.

The properties that will be compared will be taken up in the following order: (1) nature of possible targets; (2) range; (3) influence of meterological conditions on range; (4) measurable coordinates of targets; (5) accuracy and resolution in measuring coordinates; (6) noise immunity; (7) reliability; (8) dimensions, weight, power consumption; (9) manufacturing cost and operating costs.

Nature of possible targets and influence of backgrounds

The most favorable case that can be confronted by a passive radar is that of approximately equal apparent temperatures of object and background.

The primary targets for infrared equipment are bodies with an elevated thermodynamic temperature. If these bodies do not have high conductivity they create intense thermal radio radiation. /125

Passive radar can have an advantage over IR instruments if the thermodynamic temperature of object and background are low because the response of the IR instruments decreases rapidly with decrease in temperature.

Conventional radar has an advantage over passive radar in detecting weakly radiating objects against "cold" backgrounds, while IR techniques have better capabilities for detecting heat-radiating, conducting objects.

Range

Passive radar range is greatly dependent on target size, and on its contrast with the background.

Passive radar will show greater range than conventional radar and infrared equipment when working with large targets with greater contrast.

The literature indicates that the simplest airborne passive radars can detect ice against the background of the sea at a greater range than can airborne panoramic radars.

Passive radars that measure the thermal radio relief too can have a long range because there is little dependence of signal level on range in this case.

There is no question of the fact that conventional radar has the advantage when it comes to detecting good reflecting, but weakly radiating, objects, because in this case the acceptable signal level can be achieved at moderate transmitter power levels.

Passive radar range can be longer, or shorter, than that of IR instruments, depending on the nature of the target (see above).

Influence of meteorological conditions

Passive radar is only slightly subject to the influence of meteorological conditions as compared to conventional radar, because in the case of the passive radar the propagation of energy is unidirectional.

From this point of view, infrared techniques generally cannot compete with radiotechnical equipment because IR equipment cannot even cope with dense fog, let alone cloudiness and precipitation. /126

Measurable coordinates of targets

Conventional radar is better than passive radar when it comes to measurable coordinates, because single-channel passive radars cannot measure range. Moreover, passive radars, as distinguished from conventional radars, cannot directly measure the speed at which objects observed are moving.

However, interferometer passive radars can measure the difference in Doppler shifts proportional to the angular rate of displacement of the target, something that is impossible for IR instruments to do.

Accuracy and resolution

Passive surveillance radars can be compared with conventional surveillance radars when it comes to the accuracy with which angular coordinates can be measured, and can be even better than the latter if interferometer methods, or complex antenna arrays of the "cross" type, are used.

The accuracy of passive tracking radars obviously can be somewhat better than that of conventional tracking radars because passive radar is not subject to the "scintillation" effect.

Passive radars are not nearly as accurate in fixing range as conventional radars, and are poorer at doing so than IR equipment.

The angular coordinate resolution of passive radars is of the same order of magnitude as that of conventional radars because in both cases this magnitude is determined by the angular dimensions of the antenna pattern.

We should point out that this does not apply to airborne passive surveillance radars that use the principle of temporal synthesis of antennas. Their resolution is extremely high, approaching that of optical observation equipment.

IR instruments too are better than passive radars in terms of angular resolution. IR direction finders, as is known, can have a resolution of the order of minutes, something not yet achieved in the case of passive radars.

Noise immunity /127

The relative noise immunity of passive radars can be confirmed as follows.

On the one hand, passive radars are much more susceptible to the influence of noise than are conventional radars because of their high degree of sensitivity, the broadband nature of the receiving equipment, and the absence in this equipment of frequency-time selection. On the other hand, passive radars unquestionably have the advantage over conventional radars with respect to organized noise. Passive radars, because of the complete secrecy with which they work, cannot be jammed, by frequency spot jamming, or by radio relay jamming. Moreover, there no longer is the threat of the enemy using means of destruction that can home in on the radiation from radiotechnical equipment.

The noise immunity of IR equipment is less than that of passive radars because artificial noise can be generated in the IR band.

Reliability

It is difficult to make a completely comparative evaulation of reliability because of the many design differences in passive radar, conventional radar, and infrared equipment. We therefore will assume that those subassemblies and components that are common to all three are equally reliable.

Given this assumption, it can be asserted that passive radars are much more reliable than conventional radars.

The following can be asserted on the basis of available data on the reliability of individual components:

1. passive radars, as compared to conventional radars, have fewer, and more reliable, components.

Indeed, the reliability of the antenna-feeder installation for passive radars is greater because there is no danger of the breakdown that exists in the case of conventional radars. The reliability of the radiometer is greater than that of the conventional radar receiver, because the latter usually is more complicated.

Finally, the reliability of conventional radars deteriorates /128
because of the presence of a synchronizer, transmitter, and T-R switch.

We should point out that the introduction of the latest semiconductor and molelectronic techniques should make it possible to increase the reliability of passive radars even further, because electrovacuum parts can be done away with completely, something that is impossible in the case of conventional radars;

2. passive radars and IR direction finders are comparable in reliability because while the electronic section of the IR direction finder is simpler, it usually includes comparatively low-reliability optical scanning and receiver cooling systems.

Dimensions, equipment weight, power required from supply sources

The dimensions and weight of passive radars are less than those of conventional radars because passive radars do not need such heavy and cumbersome units as a transmitter and synchronizer.

The weight and size of passive radar antennas can be somewhat higher, however.

Passive radar power requirements are much lower because there is no transmitter.

We should point out that in the future passive radars can be built entirely from semiconductors (using parametric amplifiers as the h-f amplifiers, for example, semi-conductor diode frequency multipliers as pump oscillators, and tunnel diodes as heterodynes). These passive radars will require very little power from supply sources.

So far as IR instruments are concerned, their weight, dimensions, and power consumption are of the same order of magnitude as those for passive radars.

Equipment cost and economy of operation

We already have pointed out that passive radars have fewer, and simpler, components than conventional radars. This means, of course, that passive radars are cheaper to build than conventional radars. In this regard, passive radars can have an advantage over special IR /129
equipment as well, because the latter require expensive optical systems and radiation receivers.

So far as operating costs are concerned, here too passive radars have an advantage over conventional radars because, first, they require much less energy from supply sources, and, second, they can be serviced and repaired by less qualified personnel. We also should point out that passive radars have no need for equipment to protect service personnel against h-f radiation, equipment that adds to operating expenditures.

IR instruments can be equated to passive radars from an operation point of view.

* * *

Passive radar is a young branch of radioelectronics, so it is only natural that its practical achievements still lag behind its theoretical capabilities.

Nevertheless, the process of rapid introduction of passive radar equipment into the various branches of military affairs and the national economy has already begun.

This last chapter has shown that passive radars can be used successfully in a number of radioelectronic complexes for surveillance, navigational, and other purposes.

Passive radars also have been called upon to meet the demands of rapidly developing astronautics, where the use of passive radars in many cases is more advantageous than using conventional radars because of the advantages to be gained in overall dimensions, equipment weight, and electric power consumption.

Good results have been obtained in many peaceful applications of passive radar, in the fields of geophysics, hydrology, and meteorology, in particular.

Finally, it is impossible to forget still another intriguing prospect of passive radar; its potentials for use in making noncontact measurements of internal temperatures of various bodies and objects,
something that is very important in many areas of industry, medicine, /130
and in a number of the applied sciences.

Finally, an indispensable condition for the widespread use of passive radar is further technical progress.

Here the task of mastering new, shorter frequency bands, the development of new models of broadband, low-noise, h-f amplifiers, seeking ways to build passive radars more rationally, and new methods for signal processing and measuring coordinates, is an extremely urgent one.

All of this will make it possible to bring passive radar performance indices close to those potentially attainable.

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